Frequency discrimination and frequency analysis in hearing

Hoekstra, Age

FREQUENCY DISCRIMINATION AND FREQUENCY ANALYSIS IN HEARING

AGE HOEKSTRA

FREQUENCY DISCRIMINATION
AND
FREQUENCY ANALYSIS
IN HEARING

a psychophysical study of some aspects
of the normal and abnormal auditory system

STELLINGEN

I

Het juist waarneembare verschil in herhalingsfrekwentie van een bandgefilterde periodieke impulsreeks hangt af van het frekwentie analyserend vermogen van het gehoor.

II

Het ontwikkelen en invoeren van klinisch bruikbare tests om het frekwentie discriminatie en het frekwentie analyserend vermogen van het gehoor te bepalen zou een waardevolle aanvulling opleveren van de bestaande diagnostische testbatterij.

III

Om moeilijkheden bij het spraakverstaan, die het gevolg zijn van een verminderd frekwentie analyserend vermogen van het perifere gehoororgaan, te verkleinen, verdient het aanbeveling hoortoestellen te ontwikkelen waarbij akoestische signalen elektronisch zodanig gesplitst kunnen worden dat bij weergave van aangrenzende delen van het frekwentiespektrum in verschillende oren het spectrale contrast zo veel mogelijk behouden blijft na fusie in de centrale gehoorbaan.

IV

De verklaring van Backus voor het ontstaan van de zgn. "multiphonic tones" op houtblaasinstrumenten verdient, in ieder geval voor de homogene accoorden, de voorkeur boven die van Benade.

Backus, J. (1978). Multiphonic tones in the woodwind instruments. J.Acoust.Soc.Am.63, 591-599.

Benade, A.H. (1976). "Fundamentals of musical acoustics" Oxford University Press, New York.

V

In vele composities van moderne muziek wordt onvoldoende rekening gehouden met de perceptieve mogelijkheden van het gehoor en wordt de luisteraar gedwongen een passief afwachtende luisterinstelling aan te nemen in plaats van een actief verwachtende.

VI

De veronderstelling dat de gegoede middeleeuwer zoveel verschillende specerijen in zijn voedsel gebruikte om de lucht en smaak van half bedorven vlees of vis te camoufleren, is onjuist.

VII

Hoewel het begrip kwaliteit vaak moeilijk te defineren valt, mag dit geen reden zijn om kwaliteit te negeren.

VIII

Dat de huidige interieurs van oude protestantse kerken zo kil aandoen, is meer een gevolg van de overdreven nivellering van de Franse tijd dan van de reformatorische idee uit de 17e eeuw, toen immers de kerken ook sociale en culturele ontmoetingsplaatsen waren.

IX

Uit oogpunt van energiebesparing, volksgezondheid en lawaaibestrijding is het aan te bevelen een met pedalen aangedreven fietsmaaimachine in te voeren in plaats van gemotoriseerde gazonmaaiers.

X

Het in China populaire schaakspel Xiang Qí (象棋) verdient meer bekendheid in de westerse wereld. Hoewel de diepgang waarschijnlijk minder is dan die van het westerse schaakspel, maakt de meestal kortere speelduur en het levendige en uitdagende karakter het spel zeer aantrekkelijk voor de recreatieschaker.

XI

De weer toenemende belangstelling voor de amateurblaasorkesten betekent een verrijking van het Nederlandse muziekleven.

XII

Ook een slak heeft zijn gang.

A. Hoekstra

Groningen, 9 april 1979

RIJKSUNIVERSITEIT TE GRONINGEN

FREQUENCY DISCRIMINATION
AND
FREQUENCY ANALYSIS
IN HEARING

a psychophysical study of some aspects of the normal and abnormal auditory system

PROEFSCHRIFT

ter verkrijging van het doctoraat in de
wiskunde en natuurwetenschappen
aan de Rijksuniversiteit te Groningen
op gezag van de Rector Magnificus Dr.J.Borgman
in het openbaar te verdedigen
op maandag 9 april 1979
des namiddags te 4.00 uur

door

AGE HOEKSTRA

geboren te Gorredijk

PROMOTOR : PROF.DR. R.J.RITSMA
CO-PROMOTOR: PROF.DR. J.W.KUIPER
CO-REFERENT: PROF.DR.IR. R.PLOMP

The research reported in this study was carried out in the Institute of Audiology, University Hospital, Groningen and was supported by the Netherlands Organization for the Advancement of Pure Research (ZWO).

VOORWOORD

Hoewel op het titelblad van een proefschrift meestal slechts één schrijver vermeld wordt als ware het het resultaat van een onderzoek uitgevoerd door één persoon, zijn het toch de bijdragen van velen die het uiteindelijk gestalte doen krijgen. Zonder deze bijdragen zou ook het voltooien van het onderhavige onderzoek en het gereed komen van dit proefschrift een vrome wens gebleven zijn.

Dat er al sprake is van het schrijven van een proefschrift dank ik in de eerste plaats aan mijn promotor, prof. dr. R.J. Ritsma, die mij het vertrouwen geschonken heeft om gedurende vier jaar met ZWO-subsidie onderzoek te doen. Bij alle fasen van het onderzoek is hij nauw betrokken geweest en niet alleen als een betrouwbaar proefpersoon. Daarnaast past een woord van dank aan mijn co-promotor, prof. dr. J.W. Kuiper, die als leider van de werkgroep Biofysica mij tijdens mijn doctoraalstudie in de gelegenheid heeft gesteld de psychofysica van het gehoor te gaan bedrijven. Verder gaat mijn oprechte dank uit naar mijn co-referent, prof. dr. ir. R. Plomp, voor de vele uren die hij met mij aan discussie heeft willen besteden. Door de kritische kanttekeningen die hij bij de eerdere versies van dit proefschrift heeft geplaatst heeft hij aan de definitieve vorm veel bijgedragen.

Tijdens het onderzoek hebben verscheidene mensen een onmisbare rol gespeeld. Hierbij denk ik in de eerste plaats aan J.H. van Dijk, die steeds voor technische bijstand heeft gezorgd, maar die vooral door het schrijven van verschillende computerprogramma's van grote waarde is geweest. Daarnaast was dit proefschrift uiteraard niet denkbaar geweest zonder proefpersonen. W.E. Kronemeijer, H.J. Roebers en H.K. Schutte hebben vele uren luisterend in "de kast" doorgebracht. De twee eerstgenoemden namen bovendien elk een onderdeel van het onderzoek voor hun rekening als afstudeeronderwerp van hun doctoraalstudie experimentele natuurkunde. Verder ben ik veel dank verschuldigd aan een aantal leerlingen van de Dr. J. de Graafschool te Groningen en een groot aantal patienten van het Audiologisch Instituut van het Academisch Ziekenhuis te Groningen, die belangeloos hun medewerking verleenden, evenals een groot aantal medische studenten.

De eerdere versies van het manuscript werden getypt door mevr. H.C. Bunschoten-Bruins.De uiteindelijke tekst werd op snelle en accurate wijze getypt door mej. A.A. op 't Ende.

De heer M. Goslinga verzorgde het fotografische werk. Het drukken van het proefschrift was in de bekwame handen van de heer H.J.G.J. van Oorschot.
Allen dank ik voor hun bijdrage.

Het bewerken van een proefschrift heeft in het algemeen ook een ingrijpende invloed op het gezinsleven. Dat deze ontwrichting binnen de perken is gebleven is voor een belangrijk deel aan Martin te danken geweest, doordat hij vele taken van mij heeft overgenomen. Tenslotte dank ik Duifje voor de correcties van de engelse tekst, maar meer nog voor haar stimulerende op- en aanmerkingen. Zij is voor mij een voortdurende steun en toeverlaat geweest.

Het verschijnen van dit proefschrift werd mede mogelijk gemaakt door het beschikbaar stellen van faciliteiten door het Algemeen Ziekenfonds Amersfoort en Omstreken en door een bijdrage van het Audiologisch Centrum van de Prof. J.J. Groen Stichting te Amersfoort.

CONTENTS

"Soun ys noght but eyr ybroken,
And every speche that ys spoken
Lowd or pryvee, foul of fair,
In his substaunce ys but air".

Geoffrey Chaucer
The House of Fame, l.765 sqq. (c.1380)

CHAPTER 1

INTRODUCTION

1.1 General introduction

The importance of speech and hearing, pre-eminently the communication tools of man, is illustrated by many proverbs. Perception of speech is a highly complex matter which is often aggravated by the presence of ambient noise. That's why our natural hearing equipment has to be such a sophisticated system. However, a disorder of the peripheral hearing organ causes a large number of people to suffer from a perceptive hearing loss. The consequence of such a hearing impairment is often a severe loss of speech intelligibility, especially in noisy environments. It is a still unanswered question what exactly this deterioration is caused by.

When we consider speech as a sound pattern continuously changing in frequency composition, we might infer that the loss of frequency analyzing capacity is an important cause of this deficiency. A diminished frequency resolution reduces the separation of the formants, the characteristic peaks in the energy spectrum of a vowel, and renders formant transitions inaudible as a result of an excessive upward spread of masking. It further results in a deterioration in the detectability of signals in the presence of background noise and may also affect the ability to extract pitch information from the analysis of harmonic spectra (according to modern pitch theories). Accordingly, knowledge of the frequency analyzing capacity of the auditory system under pathological conditions would be valuable, especially in connection with other audiological data.

The frequency analyzing capacity is such a fundamental property of the auditory system that alterations in it should become manifest in other aspects of hearing than only speech intelligibility. To avoid the difficulties inherent in speech intelligibility measurements, it is best to investigate the frequency analyzing capacity under more elementary experimental conditions in psychophysics. There are two main methods: firstly, as a limited frequency resolution implies a reduced sensitivity to frequency shifts, frequency discrimination can inform us about frequency analysis, secondly this analyzing capacity can be measured by masking experiments. These two approaches provide us with comparable data of frequency analysis, which findings in their turn can be related to speech intelligibility scores. An understanding of the relation between frequency analysis, frequency discrimination and speech intelligibility may be beneficial to future developments of hearing aids to improve the speech intelligibility of hearing impaired listeners.

1.2 Outline of the present study

Few quantitative data have appeared in the literature concerning the relation between frequency analysis, frequency discrimination and speech intelligibility. Only the relation between pure tone frequency discrimination of hearing impaired listeners and their speech intelligibility scores had been considered when this study was initiated.

The main goal of the present study is to obtain a better insight in the analytic and discriminative capacities of hearing impaired listeners compared with normal hearing listeners. Two ways to arrive at this goal have been tried. Firstly by means of frequency discrimination of complex tones and secondly through the measurement of psychophysical tuning curves.

As frequency discrimination of complex tones is still almost unexplored, investigations with normal hearing listeners had to be carried out first. These investigations constitute a considerable part of the present study. It is tested to what extent frequency discrimination of complex tones depends on the frequency analyzing capacity of the auditory system. The newly obtained knowledge is applied in the subsequent chapters of this study to the experiments with hearing impaired listeners.

The measuring equipment and the methods and procedures used are described in chapter 2. Chapter 3 relates experiments concerning frequency discrimination of the repetition frequency of bandfiltered periodic pulsetrains. For a small number of trained normal hearing listeners, the influence of the filter frequency, the filter characteristic and the signal-to-noise ratio on this frequency discrimination are considered. Then the frequency discrimination ability is

determined for non-overlapping spectra. After this the question whether and, if so, to what extent the frequency discrimination data reflect the frequency analyzing capacity is discussed. The last section contains frequency discrimination data of untrained, normal hearing listeners.
Experiments concerning questions arisen in the previous chapter are described in chapter 4. The importance of combination tones for frequency discrimination is evaluated. Additionally, pulsation-threshold patterns of a number of selected complex tones are determined.
The chapters 5 and 6 are devoted to the hearing impaired listeners. Frequency discrimination data for the repetition frequency of bandfiltered periodic pulsetrains are presented in chapter 5. The next chapter reports on psychophysical tuning curves measured for the same hearing impaired listeners. It is discussed how these results relate to each other in terms of frequency analysis.
Chapter 7 gives a final discussion with the possible implications of the experimental results for hearing theories. A summary ends this thesis.

1.3 Review of the literature

Frequency discrimination and frequency analysis are two different abilities of the auditory system. Frequency discrimination refers to the ability of the hearing system to distinguish non-simultaneous sounds which differ in frequency. Frequency analysis denotes the ability to perceive a pure tone as a separate identity when presented simultaneously with other pure tones. The frequency differences that can be managed in frequency discrimination are much smaller than those in frequency analysis. However, it is not precluded that frequency discrimination depends upon frequency analysis.

Frequency discrimination

Normal hearing listeners

Investigators of the frequency discriminative capacities of the auditory system have confined themselves mainly to pure tones as a stimulus. There exists an extensive literature on this topic: e.g. Shower and Biddulph (1931), Harris (1952), König (1957), Ritsma (1965), Henning (1966), Nordmark (1968), Walliser (1968), Rakowski (1971), Moore 1973), Wier et al. (1977). The dependence of the just noticeable difference (jnd) in frequency is treated in these reports as a function of frequency, sensation level and stimulus duration. Also the influence of different measuring methods is covered. Some of the results have been summarized in fig. 1.1. This figure shows that there is a considerable

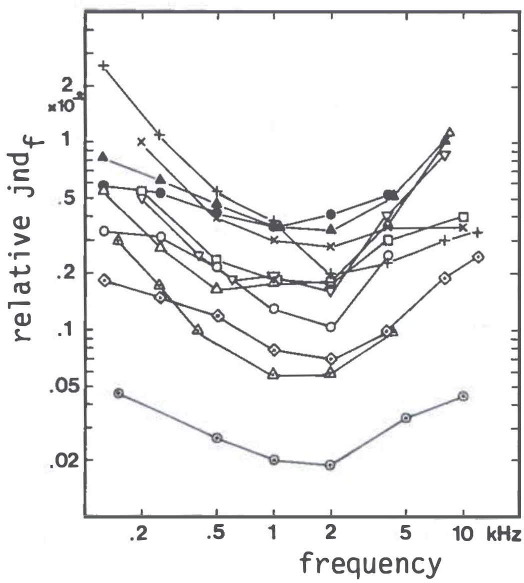


Fig. 1.1 Frequency discrimination data of pure tones of several authors for stimulus levels around 40 dB SL. The influence of the measuring method and the degree of training of the subjects can be clearly seen, though there is conformity in the shape of the curves.

+	*Shower and Biddulph, 1931*	*5 trained*	*FM*
×	*Walliser, 1968*	*7 trained*	*FM*
●	*Harris, 1952*	*large group*	*AX*
▲	*König, 1952*	*large group*	*AX*
○	*Harris, 1952*	*3 trained*	*AX*
□	*Walliser, 1968*	*7 trained*	*AX*
△	*Moore, 1973*	*3 trained*	*AX*
▽	*Wier et al.,1977*	*3 trained*	*AX*
◬	*Ritsma, 1965*	*2 trained*	*adj.*
◈	*Nordmark, 1968*	*6 trained*	*adj.*
⊙	*Rakowski, 1971*	*4 trained*	*adj.*

conformity in the shape of the curves, though the absolute values may differ according to the measuring method used and the degree of training of the subjects. The reader is referred to the above mentioned papers for details. Although several theoretical models have been proposed (Siebert, 1970; Luce and Green, 1974; Goldstein and Srulovicz, 1977) the mechanism of frequency discrimination is still a matter of research and debate. Both temporal and spectral information may be important.

Whereas pure tone frequency discrimination is heavily documented, studies concerning the frequency discrimination of complex tones are rather scarce. Confining ourselves to periodic signals there is an early study by Flanagan and Saslow (1958) concerning discrimination of formant frequency, followed by only a few later papers: Schreiber (1962), Campbell (1963), Ritsma (1965; 1971) and Walliser (1968). It can be extracted from these studies that for complex tones there is not just a single jnd for frequency. The result of a frequency discrimination measurement depends on the composition of the complex tone and on the variation applied. This is probably the reason of the seeming disagreement between different authors concerning the question of whether the jnd in the fundamental frequency of a complex tone is smaller or larger than the jnd of the corresponding pure tone.

The most comprehensive study comes from Walliser (1968). His study is concerned with the determination of the jnd in periodicity pitch, which is evoked both as the fundamental frequency of a harmonical spectrum and as the modulation frequency of an amplitude modulated pure tone. It appeared that the jnd in the fundamental frequency, Δg, corresponded closely to the jnd's of the constituting harmonics of the complex tone: $\Delta g = \text{minimum}\, \Delta f_i/i$, where g is the fundamental frequency and f_i the frequency of the i^{th} harmonic. Similarly for amplitude modulated tones the jnd of the modulation frequency was determined by the jnd of the lowest frequency component in the spectrum. This can explain that in the latter case the jnd of the complex tone is larger, in the former smaller than the jnd of the corresponding pure tone.

According to Ritsma (1965) the jnd of pitch change can be determined when separated from changes in timbre due to frequency change of the harmonics, by using stimuli consisting of

non-overlapping harmonics. The jnd for pitch of a complex tone appears to be slightly larger than the jnd for frequency of a pure tone of the same pitch.
An interesting result of Schreiber's study (1962) is that for high-pass filtered pulse trains Δg increases for $f_{co} > 10\ g$ (f_{co} is the cut-off frequency). Ritsma (1971) reports for a bandfiltered pulse train largely different jnd's in the repetition frequency for low and high repetition frequencies of this pulse train. The jnd for repetition frequency seems to increase when f exceeds 12 g (f is the filter frequency).
The conditions under which the experiments have been performed differ too much to warrant a direct comparison, but there seems to be some indication that the jnd_g depends upon the degree to which frequency components are resolvable.

As these studies are closely related to the study of the perception of pitch, a word often mentioned in the present study, for a good understanding something should be said about pitch. Pitch is that attribute of auditory sensation in terms of which sounds may be ordered on a musical scale, i.e. that attribute in which variations constitute melody. While a pure tone has normally only one pitch corresponding to its frequency (for exceptions to this rule see Houtgast, 1976), in a complex tone more pitches may be distinguished: a low pitch equal to the pitch of the fundamental frequency for a harmonic complex tone; the pitches of the harmonics that can be heard separately due to the frequency analyzing capacity of the auditory system; a percept called "rattle" pitch (Plomp, 1976) evoked by the inseparable higher harmonics. The "rattle" pitch is equal to the low pitch which is derived from the pitches of the lower harmonics that are resolved by the ear. (For a fuller account of the pitch of complex tones see De Boer (1976) or Plomp (1976).) The 4th and 5th harmonic, if present, are dominant in the determination of low pitch. Otherwise the lowest higher harmonics, including combination tones resulting from the ear's non-linearity, are preferred. The low pitch is centrally derived in a pattern-recognition process, though peripheral factors are important. The organisation of the pattern-recognition is not known. Three different models have recently been proposed to account for the derivation of a low pitch from the resolved lower harmonics of complex tones: Wightman (1973), Goldstein (1973) and Terhardt (1974). All three models include a peripheral stage characterized by a limited frequency analysis and a central stage in which the low pitch is derived. The indispensability of frequency resolution for pitch is emphasized in all three models. The central stage describing the organisation of the pattern-recognition process is different. All three models are able to account for a number of pitch phenomena.

Hearing impaired listeners

A number of investigations concerning frequency discrimination of pure tones by hearing impaired listeners are reported in the literature (Schubert, 1951; Meurman, 1954; Butler and Albrite, 1956; König, 1961; Di Carlo, 1962; Ross et al., 1965; Parker et al., 1968; Campbell, 1970; Gengel, 1969; 1973; Arlinger, 1976 and Risberg, 1978). Only a few recent studies are concerned with the frequency discrimination of complex tones (Danaher et al., 1973; Danaher and Pickett, 1975). For all frequencies considered the mean values of the jnd for frequency in hearing impaired listeners were found to be considerably larger than in normal hearing listeners. However, a division between normal and pathological frequency discrimination is not easily made because of the enormous spread in the interindividual results. Nevertheless Campbell (1970) claims that a relative jnd in frequency of 0.01 at 20 dB SL (sensation level) will distinguish the normal from the pathological when a frequency modulation technique is used. Nearly all studies use untrained hearing impaired listeners, which may be an extra source of variability. Gengel (1969) has considered the question of whether the rather poor performance is due to a lack of auditory experience. A considerable practice effect was found for many of the hearing impaired children that participated in his experiment, though some children reached maximum performance on the initial test, while others persisted to show much variability between different sessions. Similar findings were reported by Butler and Albrite (1956). Though training may reduce the difference between the results of normal hearing and hearing impaired listeners, the difference is still for the greater part caused by functional defects.

It has been suggested that the jnd for frequency increases with increasing hearing loss. Gengel (1969) and Ross et al. (1965) found a significant correlation between hearing loss and the jnd in frequency for 500 Hz, but not for other frequencies. Results of Di Carlo (1962) show similar tendencies.

Fig. 1.2 shows the combined results of several authors using different measuring methods with various kinds hearing impairment. Clearly a tendency exists towards a larger jnd

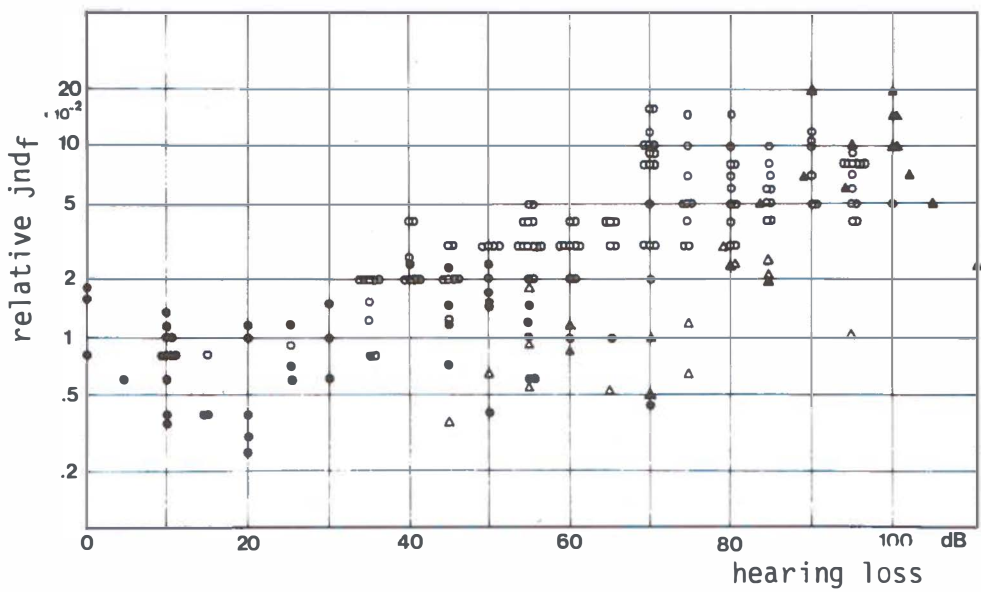


Fig. 1.2 Frequency discrimination results of hearing impaired listeners as a function of hearing loss. The data from four authors, who published individual results, are shown. The results at different pure tone frequencies are combined indiscriminately. All authors used 0.5, 1 and 2 kHz, except Gengel who used 0.5, 1.5 and 3 kHz.

●	*König, 1961*	*8 adults with different cochlear pathology (both ears)*
○	*Di Carlo, 1962*	*22 children with congenital hearing loss (both ears)*
△	*Gengel, 1973*	*5 trained children with congenital or early acquired hearing loss*
▲	*Risberg, 1978*	*6 children with congenital hearing loss*

with increasing hearing loss. The spread in the results is considerable, however: an individual hearing impaired listener can have reasonably good frequency discrimination capacities despite a large hearing loss. Leshowitz (personal communication) showed this same tendency within subjects, i.e.

the jnd in frequency is proportional to the amount of hearing loss at various frequencies, but the data of König (1961) are less unequivocal on this point.

It has been examined whether the frequency discrimination data of hearing impaired listeners correlate with the impaired speech intelligibility of these listeners. Di Carlo (1962) found only a correlation between the discrimination loss for words and the jnd in frequency at 0.5 and 1 kHz, Ross et al. (1965) on the other hand to a certain extent at 2 kHz, while Gengel (1973) found a correlation with the jnd_f at 3 kHz but not at other frequencies. That these results show so many discrepancies among themselves is not so surprising, because good speech discrimination does not necessarily depend on good frequency discrimination of pure tones. Deterioration in both types of discrimination might well be the effect of a loss of frequency analyzing capacity due to the perceptive hearing impairment. This becomes apparent in frequency discrimination experiments with complex stimuli by Danaher et al. (1973) and Danaher and Pickett (1975). Although it was found that hearing impaired listeners are able to discriminate shifts in single formants as well as changes in the frequency of pure tones, the discrimination accuracy is reduced when a low-frequency formant is added to the formant in which a shift in frequency has to be perceived. The presence of the low-frequency formant masks the frequency transition in the higher formant. In such cases good frequency analysis is necessary for good frequency discrimination. Dichotic presentation of the formants improved the discrimination score relative to the monotic condition.

Frequency analysis

Normal hearing listeners

It is generally accepted that the peripheral auditory system can be conceived of as a set of overlapping bandpass filters tuned to different frequencies. The resolving power of these auditory filters has received much attention in the literature. The psychophysical data concerning the frequency analyzing capacity of the auditory system have recently been reviewed excellently by Plomp (1976). Depending upon the experimental paradigm different values have been found. Studies by Plomp (1964) and by Plomp and Mimpen (1968) show that for complex tones the first 5 to 7 harmonics can be separately identified. This means that to hear out a particular harmonic the frequencies of neighbouring harmonics should be about 15 to 20% apart. A similar result was reported by Moore (1972) in a slightly different experimental paradigm. This limit agrees quite well with the critical bandwidth (Zwicker and Feldtkeller, 1967). When the complex signal consists of only two tones, however, the frequency separation needs to be only about half as large to hear both tones separately, except at high frequencies (Plomp, 1964; Plomp and Mimpen, 1968). The same applies for the identification of the lowest partial of a multi-tone complex (Moore, 1972). Still finer frequency resolution was reported by Cardozo (1967) and Duifhuis (1972), using a special way of drawing the observer's attention to a particular harmonic. Their stimulus was, however, of a dynamic nature, whereas the stimuli used by the previously mentioned authors were steady state.

Another way to find the limit of the frequency analyzing capacity of the auditory system was explored by Houtgast (1974) by measuring the resolved contrast in a rippled noise masker as a function of the ripple density. From these data the bandwidth of the auditory filter can be calculated. It appeared that the calculated bandwidth depends on whether the probe tone is presented simultaneously or non-simultaneously with the masking noise. In the latter condition the bandwidth is about twice as small as in the former. The difference is attributed to lateral suppression. Lateral suppression is the phenomenon that the activity elicited by a tone in isolation can be decreased through the presence of another tone. In a simultaneous masking paradigm the probe tone is suppressed, whereas in a non-simultaneous procedure it evades suppression, thus accounting for the different results (Houtgast, 1974). The existence of lateral suppression implies that the auditory filter is not just a simple linear filter.

On the basis of the substantial discrepancy between mechanical and neural frequency selectivity and on other grounds Evans and Wilson (1973) have suggested that cochlear filtering is a two-stage process: a mechanical filter (basilar membrane) is followed by a physiologically vulnerable second filter. A non-linear process is envisaged to be "sandwiched" between the two filters to account for lateral suppression and the existence of combination tones. The agreement between the bandwidth estimates of the cochlear filter derived from cochlear nerve, behavioural and psychophysical data is such that it may be concluded that the frequency selectivity of of the auditory system is already determined at the level of the cochlear nerve (Evans and Wilson, 1973).

Hearing impaired listeners

The high susceptibility of the "second filter" to deleterious influences as metabolic disturbances, toxic agents and other factors makes it plausible that frequency selectivity becomes degraded in cases of cochlear impairment (Evans, 1974). A number of psychophysical studies are consistent with this idea. There is some evidence for a widened critical band (De Boer, 1959; Scharf and Hellman, 1966) and for increased upward spread of masking (Martin and Pickett, 1970; De Boer and Bouwmeester, 1974) with hearing impaired listeners. These findings may be accounted for by the loss of the sharply tuned segment of frequency threshold curves of single cochlear nerve fibres. When the present study was nearly completed a number of reports appeared on tone-on-tone masking paradigms, the measurement of the psychophysical tuning curve (Leshowitz and Lindstrom, 1977; Schorn et al., 1977; Wightman et al., 1977) with hearing impaired listeners.With a similar paradigm also electrocochleographic recordings were made in such patients (Eggermont, 1977). Measurements of the resolved contrast in rippled noise have also recently been published (Pick et al., 1977) showing a deterioration of frequency selectivity. The results of these recent studies will be discussed in chapter 6 together with our own data on this topic.

CHAPTER 2

APPARATUS, METHODS AND PROCEDURES

2.1 Apparatus

For the many different experiments that are described in the following chapters, a number of different configurations of the measuring equipment was used. Experiments in the earlier stages of the investigation, for instance those of section 3.2, were performed with analogue apparatus only, whereas later a small digital laboratory computer (DEC Lab 8 E) was used in combination with the analogue apparatus. The computer not only controlled the experiment, but was also used for the generation of complex signals, in particular those signals that could not be obtained with our analogue equipment.

The various experimental configurations will now be described separately with reference to the chapters or paragraphs in which they are used. Common to all experiments is the observer sitting in a soundproof cabin and listening to the stimuli. These are presented, after proper amplification, through headphones (TDH 49) with circumaural cushions (GS 001A) either binaurally or monaurally. The frequency response of the headphone is shown in fig. 2.1. This response is

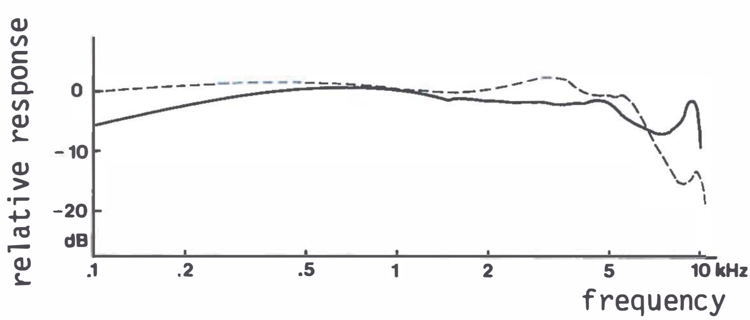


Fig. 2.1 The frequency response of the headphone TDH 49. The solid line represents the response of the headphone mounted with circumaural cushions (GS 001A) on a flat-plate coupler. The response on a 6 cm^3 coupler is given by the dashed line.

determined with a flat-plate coupler as originally was used with circumaural earphones by Shaw and Thiessen (1962). The cushion was partially filled with cottonwool to prevent resonance effects or reduce them as much as possible. The flatness of the frequency response allows the use of frequencies up to 5 kHz without much difficulty. Resonances of the enclosed airvolume between headphone and ear may contaminate the use of higher frequencies (Shaw, 1965). The spectra of the stimuli may be affected considerably in this frequency region. Fig. 2.1 shows also the response of the headphone determined with the conventional 6 cm^3 coupler. The electrical input of the headphone could continuously be monitored with an oscilloscope and a real-time spectrum analyser (Ubiquitous UA6B). Hum and distortion products of the apparatus were always more than 45 dB below the signal level.

In all frequency discrimination experiments with normal hearing listeners the stimuli were presented in 600 msec observation intervals separated by a silent interval of the same duration. As a rule the presentation of the stimuli was diotically,i.e. the same stimulus presented to either ear, at 40 dB SL. Every new stimulus pair was initiated by the observer's pressing a button. A maximal degree of concentration could thus be achieved. Responses had to be given by pressing one of the two response push-buttons in a forced choice arrangement. Visual feedback about the correctness of each response followed immediately. This assures a willing cooperation of the observer and leads to short learning periods.

For the basic frequency discrimination experiments (section 3.2) the instrumental set-up was as follows (fig. 2.2). A pulse generator (Philips PM 5711) is triggered by each one of the two oscillators (HP 4204 A) in turns. The sequence is determined by the AX-monitor. This AX-monitor randomises the presentation order and collects the responses. The pulse trains generated by the pulse generator are then fed into a 1/3-octave filter and there upon into the headphone after proper amplification. In most experiments with this basic instrumental set-up the 1/3-octave filter was a Bruel & Kjaer 1615. This filter has an attenuation rate outside the passband gradually decreasing from 120 dB/oct. to 75 dB/oct. for frequencies of 1.12 (or 0.9) to 1.75 (or 0.55) times the centre frequency. This gives an average slope steepness of about 100 dB/oct. In the experiments reported in section 3.3 this particular filter is replaced by other filtercombinations,

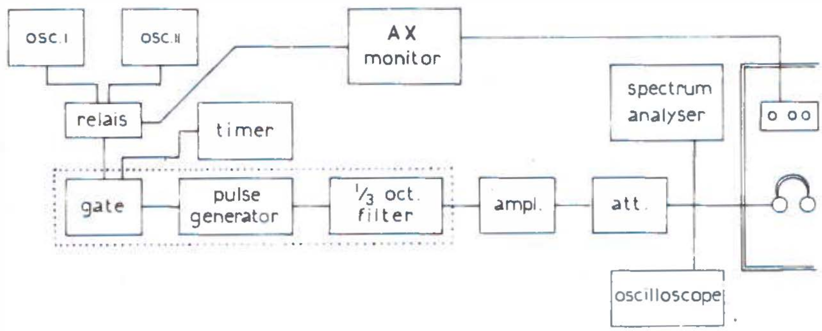


Fig. 2.2 A block diagram of the apparatus used for the basic frequency discrimination experiments. The part of the apparatus enclosed within the dotted line may be substituted by the configurations of fig. 2.3a, b or c.

viz. two Krohn Hite 3550 bandpass filters in series, one B & K 1615 and two KH 3550 bandpass filters in series and two B & K 1615 1/3-octave filters in series yielding approximate slope steepnesses of 50 dB/oct, 150 dB/oct and 200 dB/oct respectively.

The experiments of section 3.4 and 4.1 require a noise source. The basic equipment of fig. 2.2 was therefore slightly modified. Either fig. 2.3a or fig. 2.3b should be substituted for the part of the apparatus of fig. 2.2 enclosed by the dotted line. The noise source of fig. 2.3a was a "maximum length sequence generator" (HP 3722A) - the sequence length used was 2^{20} - 1 bits, with a bit duration of 10 μsec - triggered externally to provide for synchrony of pulse train and noise burst. Every observation interval thus contains exactly the same noise background. The noise source of fig. 2.3b was a white noise generator (B & K 1402) and the noise filter could be bandpass, lowpass or highpass. The noise was presented either simultaneously with the pulse trains or continuously. This condition with a LP-noise filter was used in chapter 5 with the hearing impaired listeners.

The last experiment in which only analogue apparatus was used, concerns the discrimination of the repetition rate of chopped noise (section 3.2). In this case fig. 2.3c must be substituted for the part within dotted lines of fig. 2.2. The pulse generator triggers an interval timer (GS 472) control-

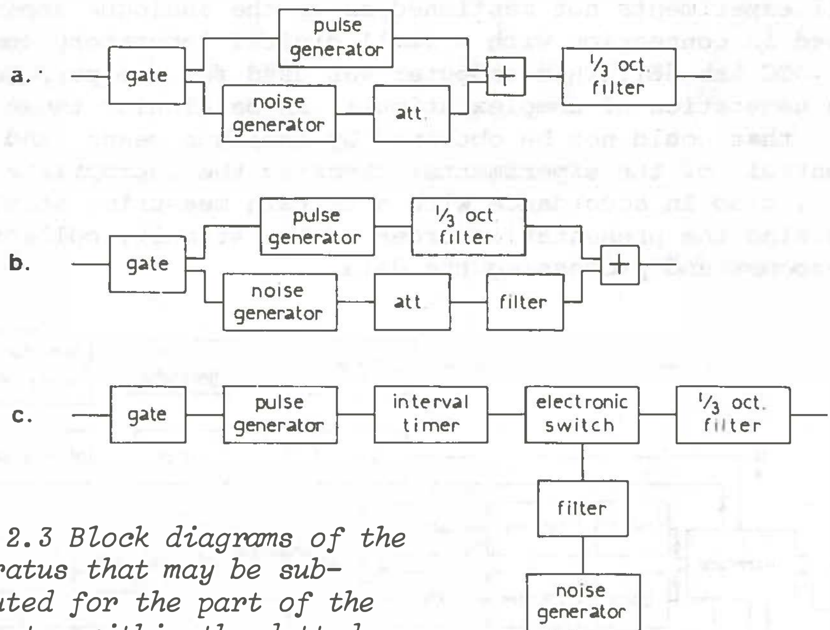


Fig. 2.3 Block diagrams of the apparatus that may be substituted for the part of the apparatus within the dotted lines of fig. 2.2.
a. substitute equipment for the experiments of section 3.4
b. substitute equipment for the experiments of section 4.1 and of chapter 5
c. substitute equipment for the frequency discrimination experiments with chopped noise of section 3.2

ling in turn an electronic switch (GS 829E). This switch (rise-decay time: 10 μsec; duty cycle adjustable) chops a broadband filtered noise periodically. This chopped noise is presented to the observer after bandpass filtering through a 1/3-octave filter. This filtering takes place to limit the stimulated frequency region and to allow a close comparison with the frequency discrimination results of the periodic pulse trains. Using this particular apparatus the broadband prefiltering of the white noise (4 octaves round the centre frequency of the 1/3-octave filter; slopes of 24 dB/oct.) was necessary in order to keep clicks due to the switching-on-and-off of the noise more than 45 dB below the signal level. The bandwidth used is, however, large enough to prevent any spectral information related to the switching rate.

For all experiments not mentioned above the analogue apparatus was used in connection with a small digital laboratory computer (DEC Lab 8E). This computer was used for two purposes: a. the generation of complex stimuli, in particular those stimuli that could not be obtained by analogue means, and b. the control of the experiments: choosing the appropriate stimuli, also in accordance with a certain measuring strategy, randomising the presentation order of the stimuli, collecting the responses and processing the data.

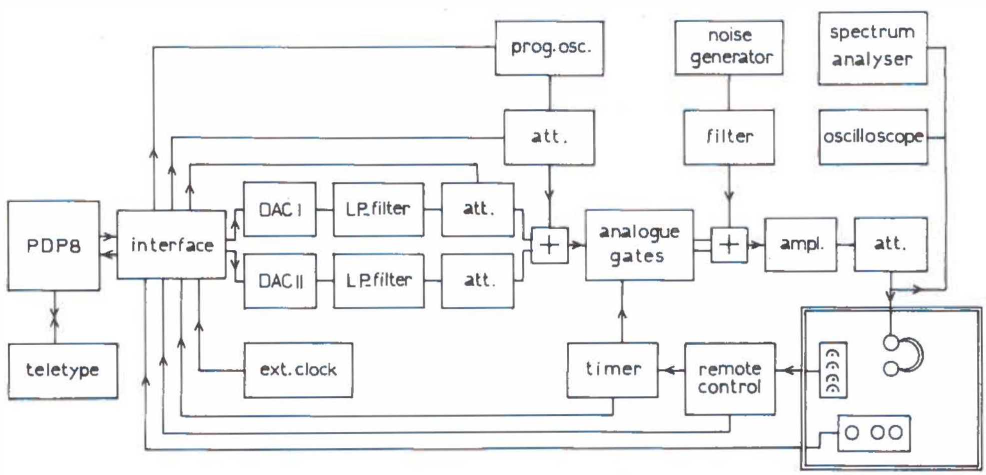


Fig. 2.4 Block diagram of the apparatus used in connection with the digital computer. Communication with the computer occurs either via the teletype or via remote control switches. The external clock governs the rate at which the DA-conversion is performed. The analogue gates provide for the smooth in- and outfading of the stimuli (rise-fall times 25 msec). The timer controls the different time sequences that are required in the various experiments.

As to the generation of the signals: one period of a wanted signal was divided into a number of intervals and the amplitude value of the signal waveform in every interval calculated. These calculated amplitude values were stored in memory. A number of signals was kept in core in this way and could be called for under program control either via a teletype or by the manipulation of remote switches. To retrieve the analogue waveform of such a signal a Digital-to-Analogue conversion

was performed at a rate of 4 times the eventually audible mean signal frequency with a 10 bit DA-converter. Appropriate lowpass filtering (2 KH 3550 bandpass filters in series) removed all aliasing products.
The complete experimental set-up is given in the block diagram of fig. 2.4. Different combinations of the instruments available were used to suit the purpose of the various experiments.

2.2 Methods

For the frequency discrimination experiments two measuring strategies were used, viz. the AX-method and the PEST-method. Both are adaptive forced-choice procedures differing slightly in the rules of their measuring strategy and the determination of the final results.

The AX-method, introduced at the IPO at Eindhoven (Cardozo, 1966), consists of a variable number of trials. In every trial the observer listens to two successive tone bursts denoted by A and X. After each pair of tones it must be decided whether the sequence was AX or XA. The two possible orders were randomised. In a variant the decision had to be made between the sequences AA and AX. The next trial is made for the same or a different stimulus condition according to the measuring strategy as explained below. The initial frequency difference between the tone bursts is large in order to be easily perceivable for the observer. After 5 correct decisions the frequency difference is halved and the observer is tested on this new level. Halving of the difference is also done after one incorrect combined with 7 correct responses or after two incorrect with 9 correct responses. After 4 incorrect responses, however, the frequency difference is doubled. The combination of 3 incorrect and 9 correct responses leads to a testrepetition at the same level. After 6 to 10 direction changes (from halving to doubling or vice versa) the test is terminated. The threshold value or just noticeable difference for frequency (jnd_f) is given by the mean level after which the frequency difference had to be doubled, multiplied by $\sqrt{2}$. It can be shown that at this level the probability of correct response equals 70%. On the average one threshold determination involves about 100 trials. In this method a fair compromise is reached between test duration and test accuracy.

The PEST (Parameter Estimation by Sequential Testing)-

method was introduced by Taylor and Creelman (1967) with the aim of efficient threshold estimination. A number of rules is used to determine the levels at which trials are successively made. The number of trials at each level depends on the correctness of the responses and the required degree of confidence. The first level (in our case the initial frequency difference between the stimuli) may be chosen arbitrarily. After some trials the next test level is found by adding or subtracting a certain amount (the initial stepsize) to or from the previous level. Every change from reduction to augmentation of the frequency difference or vice versa causes the stepsize to be halved until it equals a predetermined final stepsize. The test is then terminated and the level last encountered is taken as the threshold level. The efficiency of threshold determination with the same accuracy will be increased by reduction of final stepsize in particular (Hall, 1974). The number of trials per test was on the average about 70. The PEST-method was only used for the experiments of section 3.5 and for a part of the experiments of section 4.1. No essential differences were found in the results obtained with both methods (compare section 3.2 with section 3.5).

2.3 Procedures of the masking experiments

Apart from the frequency discrimination experiments, a number of other experiments was performed, viz. the measurement of pulsation-threshold patterns, of psychophysical tuning curves and of the resolved contrast in a rippled noise masker. In the following we will give a short description of the procedure of each of these experiments.

The pulsation-threshold method

The pulsation-threshold method introduced by Houtgast (1972) is now a generally recognized tool in psycho-acoustics. In the pulsation-threshold method a masking tone and a test tone are alternated. Depending on the specific relations between the masking tone and the test tone, the test tone will be perceived either pulsating or continuous. The boundary between the two percepts is called the pulsation-threshold. The method can be used to obtain pulsation-threshold patterns of complex tones. Pulsation-threshold patterns resemble very much ordinary masking patterns. The pulsation-threshold method differs, however, essentially from a masking method in that it is based on a continuity effect rather than a masking effect.Whereas in a masking experiment the presence of the masking tone influences the detectability of the test tone, in the pulsation-threshold method the temporal character of the test tone is modified. Because the masking tone and the test tone sound non-simultaneously the pulsation-threshold method reveals effects of lateral suppression.

In the actual experiment the repetition rate of the alternation is 4 Hz. Both test tone and masking tone are gated trapezoidally with rise and decay times of 10 msec. The observer has to adjust the level of the test tone until this tone (though physically still interrupted) sounds continuous to him. With a masker fixed in level and frequency, this is done for a number of relevant test tone frequencies. In our experiments the masker was either a pure or a complex tone. For ease of measurement every 8th test tone burst was omitted from the sequence. Besides the adjustment procedure a Békèsy up-down procedure was used to establish the pulsation-threshold.

In the adjustment procedure the observer controls the level of the test tone by turning the knob of an attenuator while masker and test tone are alternated continually. The level of the test tone should be so adjusted that the pulsating character of the test tone bursts is just not perceived. In many instances, however, especially with complex maskers, this presents some difficulty because the course from clearly pulsating to unequivocally continuous may be a long one. Observers are often not satisfied with their ultimate adjustment. To alleviate their uncertainty a Békèsy up-down procedure was used. The level of the test tone now changes automatically every two seconds by 1 dB (after an initial period in which the steps were 5 dB to reach the relevant region quickly). The observer can only control the direction of the change by pushing or releasing a button. When he perceives the test tone as clearly pulsating he pushes the button and releases it when the test tone sounds clearly continuous. The sound levels of the test tone at the turning points are averaged to yield the threshold value. The results of both methods are in agreement.

Psychophysical tuning curves and rippled noise masking

In chapter 6 experiments are described to measure psychophysical tuning curves and to obtain rippled noise masking data. In both cases a direct masking paradigm is used. For the determination of the psychophysical tuning curve the test tone was fixed in level (approximately 10 dB SL) and frequency. The test tone was presented twice a second (duration: 30 msec, rise-fall time: 5 msec; interval in between: 120 msec) simultaneously with the masking tone, which lasted for 800 msec and was repeated every second (see fig. 2.5). The doubling of the test tone is used to get a clearer contrast with the sequence of masker bursts. It appeared to be quite helpful

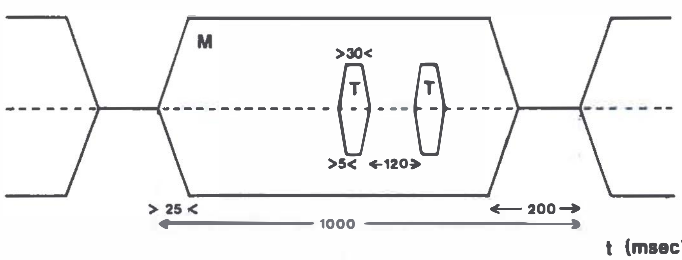


Fig. 2.5 Time sequence of masking tone and test tone pair as used for the determination of psychophysical tuning curves and for the measurements of the resolved contrast in a rippled noise masker.

to inexperienced listeners especially. Test tone and masking tone were phase-locked to each other, except for f_T=4 kHz. Advantages of the phase locking technique are described by Vogten (1974). Our own measurements with and without phase-locking resulted, however, in about the same threshold values. Only the detection criterion was somewhat unstable in the latter case due to the changing phase relation between test tone and masking tone, thereby influencing the measuring accuracy. In the Békèsy up-down procedure the observer controls the increase or decrease of the level of the masking tone by releasing or pressing a button. This level must be increased when the test tones are audible and decreased when the test tones are inaudible. The mean sound level at the turning points constitutes the threshold of audibility of the test tones. The whole procedure is repeated for a number of masker tone frequencies around the test tone frequency. Connection of the respective threshold levels of the masker tones yields the psychophysical tuning curve. A continuous (LP-) noise could be added to eliminate the possible influence of distortion products of the ear on the threshold of audibility of the test tones.

Rippled noise is a noise with a power spectrum that is cosine shaped along a linear frequency scale. It is obtained by adding white noise and its delayed repetition. By changing the delay time the ripple density, i.e. the number of peaks in the power spectrum per unit frequency interval, is altered. Changing the polarity of the noise results in an inversion of peaks and valleys in the power spectrum. In the masking experiments the test tone is fixed in level and frequency. The noise is arranged in such a way that a peak in the power spectrum coincides with the test tone frequency. The level of the noise is changed again in the Békèsy up-down procedure around the threshold of audibility of the test tone. The threshold value is calculated from the turning points as before. Next the polarity of the delayed noise is reversed so that now a valley coincides with the test tone frequency. The threshold of audibility of the test tone is again established with the Békèsy up-down procedure. Finally, the threshold noise levels are subtracted to give a value for the resolved contrast between a peak and a valley. The resolved contrast is found to diminish for increasing peak numbers, i.e. for increasing delay times. These measurements give therefore information about the resolving power of the ear. In the actual measurements the different peak numbers coinciding with the test tone frequency were randomized, but measurements at the corresponding peak and valley were always made successively to avoid criterion changes as much as possible.

CHAPTER 3

FREQUENCY DISCRIMINATION FOR BANDFILTERED PERIODIC PULSETRAINS

3.1 Introduction

When the analytic and the discriminative capacities of the auditory system have to be investigated, frequency discrimination experiments are valuable, in particular frequency discrimination of complex tones. As already mentioned in chapter 1 frequency discrimination of complex tones has received relatively little attention in the literature. There is no thorough study that relates frequency discrimination to the resolvability of the frequency components of a complex tone. This chapter is an attempt to fill this gap in the literature. In the present study we have restricted ourselves to the use of harmonic complex tones, viz. complex tones of which the frequencies of the components are multiples of a common divisor, the fundamental frequency.

The main stimulus used in the experiments of this chapter is the bandfiltered periodic pulse train. Bandfiltering restricts the stimulated frequency region. By changing the repetition frequency the frequency separation between the harmonics within this frequency band may be varied. The resolvability of the harmonics of this complex tone is thus influenced by the choice of the repetition frequency relative to the filter-frequency. By measuring the jnd in the repetition frequency for different repetition frequencies, the influence of the degree of frequency resolution of the complex tone on frequency discrimination can be investigated. The experiments have been performed with a small number of trained normal hearing listeners.

A periodic pulsetrain consists of a regular sequence of short pressure pulses. The time interval T between two successive pulses is the period of the pulsetrain and equals $1/g$, where g is the repetition frequency. The power spectrum of this stimulus is an equidistant line spectrum on a linear frequency scale. The spectral lines are situated at multiples of g. The amplitudes of these harmonics depend on the pulse-width τ in relation to the period T. In formula the amplitude of the n^{th} harmonic is:

$A_n = \frac{V\,\tau}{T} \cdot \frac{\sin x}{x}$, with $x = \pi\, n\, \tau/T$ and V standing for the pulse-height (Papoulis, 1962). For $\frac{\tau}{T} << 1$ the spectrum is fairly flat over a large number of harmonics: -3 dB point at $f = \frac{0,6}{\tau}$. A certain frequency region may be picked out from the broad spectrum by bandfiltering of the periodic pulsetrain. We used filters with a bandwidth of 1/3-octave, being roughly equal to the critical bandwidth of the auditory system. For filter centre frequencies up to 4 kHz τ = 100 μsec was used and τ = 50 μsec for the higher filter centre frequencies.

The subjective sensation elicited by a bandfiltered periodic pulsetrain depends on its particular composition. Under special conditions some of the lower harmonics of the periodic pulsetrain may be heard individually, but usually the signal is perceived as a whole having a definite pitch. The filter frequency or more generally the filter characteric determines the timbre of the bandfiltered pulsetrain. The timbre is low and dull for low f and high and sharp for high f. The repetition frequency corresponds to the pitch of the bandfiltered pulsetrain. For very low g the sensation is like a rattle. With increasing g, a sensation of roughness will gradually make way for a low pitch, changing into a chirping sound for very high g. Although the ear always tries to assign a pitch to such a signal, the pitch needs not necessarily govern the frequency discrimination. As frequency analysis is also a major factor in pitch perception, the prominence of pitch and the accuracy with which frequency discrimination is possible could show resemblances.

Using this kind of stimulus we are confronted with a considerable number of variables:

- First of all we are interested in the repetition frequency as a variable. The measurement of the jnd in repetition frequency (jnd_g) for different repetition frequencies for a given filter frequency is reported in section 3.2.
- Secondly, the influence of the filter frequency on the jnd_g is also discussed in section 3.2. The influence of sensation level and phase spectrum on the jnd_g is briefly mentioned in this section.
- Thirdly, section 3.3 is devoted to the influence of the filter characteristic on the discrimination of small changes in the repetition frequency. This ends up with a short investigation

into the discriminability of variations in the filter frequency.

- Fourthly, the influence of the addition of noise in the same frequency band as the bandfiltered periodic pulsetrain is investigated in section 3.4; for various repetition frequencies the jnd_g is measured as a function of the signal-to-noise ratio.
- Fifthly, section 3.5 is concerned with the discrimination of changes in the repetition frequency of pulsetrains filtered in widely different frequency bands.

Section 3.6 contains an evalution of what evidence has been gathered in favour of the relation between frequency discrimination and frequency analysis.
Finally, a short test procedure, devised as a screening test for frequency discrimination, is tried out for untrained normal hearing listeners in section 3.7.

3.2 Frequency discrimination of the repetition frequency; influence of the filter frequency

In this experiment the just noticeable difference in repetition frequency (jnd_g) of a bandfiltered periodic pulsetrain was measured as a function of the repetition frequency (g) for a number of filter frequencies (f). The apparatus used was described in chapter 2 (see fig. 2.2). The slope steepness of the 1/3-octave bandfilter (B & K 1615) was roughly 100 dB/oct. Stimuli were presented diotically at 40 dB SL. For repetition frequencies below 50 Hz the observation intervals were doubled with respect to the normal duration of 600 msec to prevent artifacts. A forced choice method was used to obtain the data (see section 2.2 AX-method). The observer had to indicate whether a sequence AX or XA was presented to him. The pairs were randomized. The observers were free to establish their own discrimination criterion, which might be pitch, timbre, rattle rate etc. Three trained observers participated in all experiments, whereas for some experiments a fourth observer was added. The determination of one threshold value (jnd_g) took about 10 to 15 minutes. The number of jnd_g's that were determined within one session varied. Repeated determinations of the jnd_g in the same stimulus condition were always carried out on separate days.

The data of all observers for a filter frequency of 2 kHz are given in fig. 3.1. This figure shows the interindividual

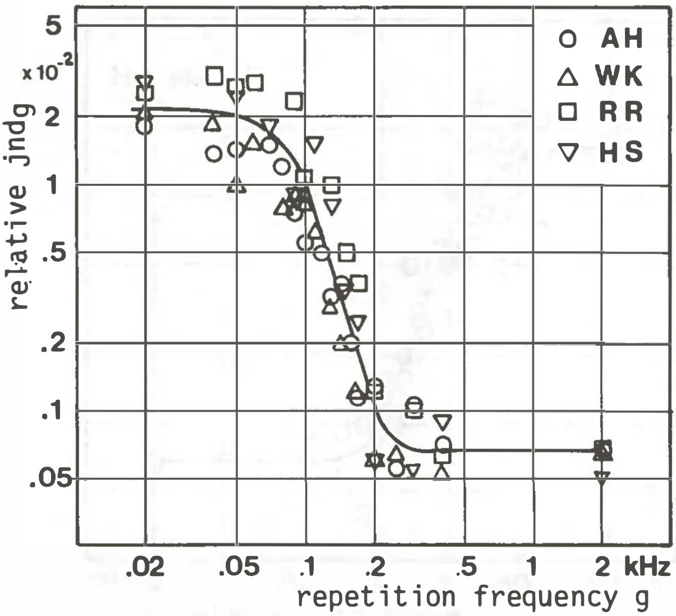


Fig. 3.1 The just noticeable difference in repetition frequency of bandfiltered periodic pulsetrains as a function of the repetition frequency. The data of four observers show the interindividual spread. Filter characteristics: f = 2 kHz, B = 1/3-octave, S = 100 dB/oct.

spread. Intra-individual spread is shown for one observer in fig. 3.2. This figure is typical for all subjects. The solid lines in the figures have been fitted by eye to the datapoints. As may be seen from these figures there appear to be three distinguishable regions of frequency discrimination. For high g the jnd_g is small, equal to the jnd_f of a pure tone. On the other hand a much worse frequency discrimination threshold, equal to about 2 per cent of g, is found for low g. In between is a region in which the relative jnd_g increases rapidly for decreasing g.
In a certain sense also the subjective impressions of the observers are in accordance with the frequency discrimination results. For the higher g values the stimuli are discriminated on the basis of their pitch difference. This becomes increasingly difficult as the repetition frequency is lowered, until rattle rate provides a better discrimination criterion.

The repetition frequencies for which jnd_g's have been determined were integer as well as non-integer fractions of

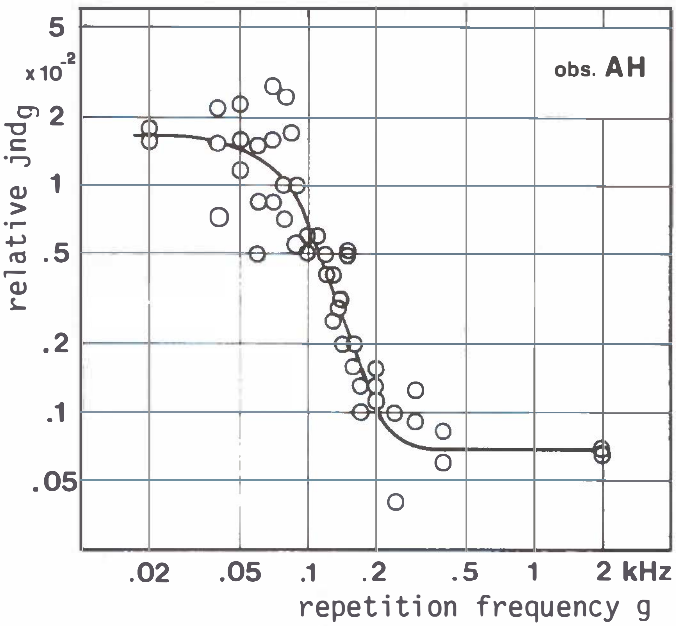


Fig. 3.2 Frequency discrimination data of one observer showing the intra-individual spread. Filter characteristics as in fig. 3.1.

the filter frequency. The distribution of harmonics within the passband of the filter is thus not limited to a symmetrical configuration only. The data show that a symmetrical configuration does not yield systematically better results than other configurations.

The measurements were repeated for other filter frequencies, viz. f = 1, 4, 6.3 and 8 kHz (for 3 observers) and additionally for f = 10 kHz for one observer. The results averaged over all subjects are reproduced in fig. 3.3. It turns out that a similar relation exists between the relative jnd_g and g for all f, viz. two plateaus of constant discrimination level connected by a transition region. The transition region becomes marginal in the case of f = 8 kHz.

The jnd_f's for pure tones (g = f) are in agreement with the literature (see section 1.3).

For the complex tones different discrimination results may be obtained for the same repetition frequency, depending on the filter frequency.

The upper plateau at $\Delta g/g \sim 0.02$ is the same for all filter frequencies.

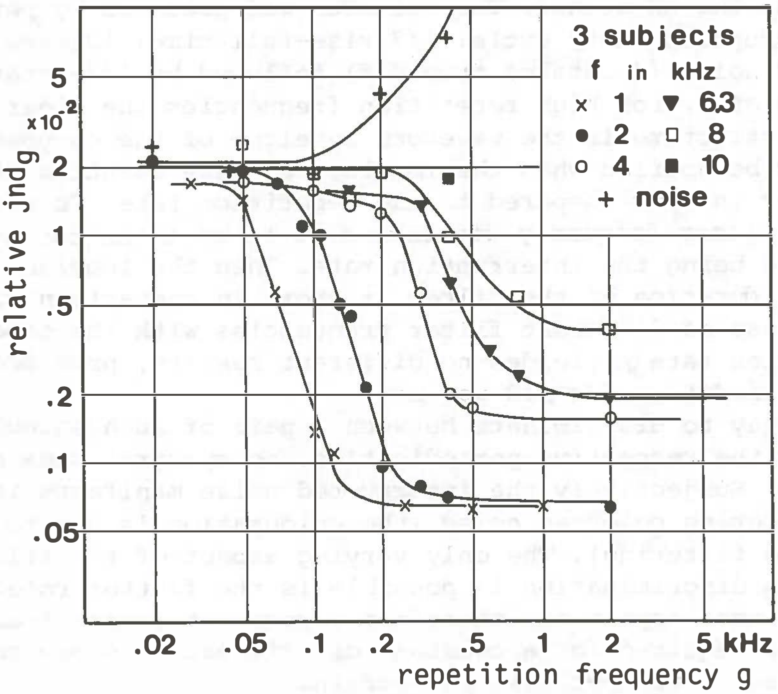


Fig. 3.3 The jnd_g *averaged over 3 observers for different filter frequencies. Filter characteristics as in fig. 3.1. The curves have been fitted by eye to the data points. (For the higher filter frequencies the curves have been extrapolated to the pure tone frequency).*

The subjective impressions of the observers for these filter frequencies are similar to those described for f = 2 kHz. Pitch sensation wanes, however, for the highest filter frequencies: the pulsetrains sound ever more chirping and discrimination is done subjectively upon timbre changes rather than upon pitch changes, although a distinction between the two is not easily made. For the same repetition frequency the timbre changes with the filter frequency, but not so the pitch, provided that a pitch exists.

The constant discrimination level at $\Delta g/g \sim 0.02$, independent of the repetition frequency provided that $n > 20$, required a closer investigation. This led to an experiment in which the jnd in repetition frequency of periodically interrupted noise was determined. The measuring equipment has been described in chapter 2 (figs.2.2 and 2.3c). The measuring

method was the AX-method. The stimulus was produced by periodic interruption (duty cycle: 1/3;rise-fall time: 10 μ sec) of wide band noise (4 octaves around f) followed by 1/3-octave filtering at f. For high repetition frequencies the clear periodic structure in the waveform envelope of the chopped noise may be spoiled when the impulse response duration of the filter is long compared to the repetition rate. To prevent this the filter frequency was increased to meet the condition $f/g \geq 10$, g being the interruption rate. Then the impulse response duration of the filter is short in comparison with 1/g. The use of different filter frequencies with the same interruption rate g, yielded no different results, provided that the condition $f/g \geq 10$ was met.
The only way to discriminate between a pair of such stimuli is comparing the respective periodicities, no spectral cues being available. Subjectively the interrupted noise manifests itself as a fluttering coloured noise (the colouration is due to the 1/3-octave filtering). The only varying aspect of the stimuli upon which discrimination is possible is the flutter rate. This is a weak aspect and therefore a somewhat longer traning period was required for a constant discrimination score than in the case of the periodic pulsetrain.
The average results for the same three observers that participated in the former experiments, are given in fig. 3.3 too. For $g \leq 100$ Hz the relative jnd_g for periodically interrupted noise equals 0.02, the same discrimination value as was found for periodic pulsetrains for corresponding repetition frequencies, if $f/g > 20$ applied. For $g > 100$ Hz the jnd_g for periodically interrupted noise increases sharply. At g = 800 Hz or higher the relative jnd_g becomes so large that the determination is meaningless (> 0.32). This fits the subjective impression that the periodically interrupted noise resembles unaffected noise more and more for higher repetition frequencies (see also Bilsen, 1968).

The above mentioned experiments were all carried out at 40 dB SL. The influence of the sensation level on the frequency discrimination of the repetition frequency of periodic pulsetrains was only incidentally investigated for f = 2 kHz. Decreasing the sensation level to 30 and 20 dB SL yielded virtually the same results as for 40 dB SL. A few exceptions towards better discrimination were found at 20 dB SL for $10 < n < 20$. It is likely, however, that irregularities in the hearing threshold may have influenced the results. Frequency

discrimination at low S/N-ratios will be treated more thoroughly in section 3.4.
The use of higher sensation levels causes not only a broadening of the stimulated frequency region but also makes distortion products of the apparatus audible. It is therefore not a priori clear whether the same aspect of the stimuli will determine the discrimination results at all sensation levels. But provided that the signal-to-noise ratio is kept at 40 dB by using a flat noise background, we could not find significant differences in frequency discrimination up to a level of 70 dB SL.

Changing the phase relation between the individual harmonics constituting the bandfiltered pulsetrain would change the waveform but not its power spectrum. Due to the great number of harmonics the influence of the phase relation could not be investigated systematically. In general, the influence of the phase relationship between the harmonics on the jnd_g appeared to be small. In section 4.2 the influence of phase changes on the pulsation threshold pattern of a three-tone complex will be shown.

Discussion

The main experimental result emerging in this section is the appearance of a typical sigmoid curve, consisting of two plateaus of constant discrimination level connected by a transition region. This curve is not confined to a particular filter frequency but is very similar for all filter frequencies investigated. The frequency discrimination threshold is not a constant for a given repetition frequency. The ratio between the repetition frequency and the filter frequency is of major importance. This is shown in fig. 3.4. The relative jnd_g-values are plotted as a function of $n = f/g$, i.e. the number of the harmonic coinciding with the filter frequency if n is an integer. The similarity of the curves is conspicuous. The upper plateau appears to be independent of f, whereas the lower plateau depends on f according to the dependence of the jnd_f on frequency. The location of the transition region with respect to the n-axis is the same for all f.
These findings are qualitatively in agreement with our expectations: good frequency discrimination when the harmonics are widely separated and a quick deterioration in discrimination

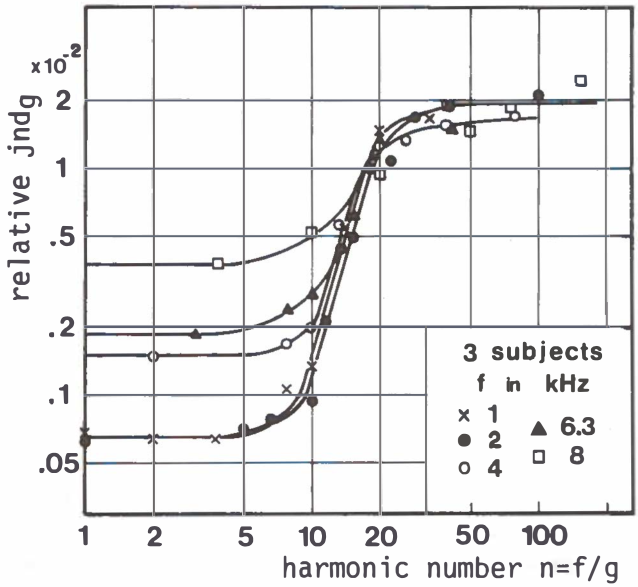


Fig. 3.4 The frequency discrimination data of fig. 3.3 plotted as a function of $n = f/g$.

score when the harmonics approach each other. For high harmonic numbers ($n > 20$) another discrimination mechanism seems to take over, so that we must assume that two different discrimination mechanisms are involved: a mechanism operating as long as harmonics can be resolved yields small jnd_g's, while another mechanism limits the deterioration in the jnd_g when the harmonics cannot be resolved any more. Later on we will deal with the lower plateau and the transition region, but we will focus our attention first on the upper level.

The upper level (for $n > 20$) is found to be constant over two decades in repetition frequency, when we follow it across different filter frequencies to fit the condition $n > 20$. For repetition frequencies below 100 Hz the level coincides with the rate discrimination curve of chopped noise (see fig. 3.3). This suggests a common discrimination criterion. Above 100 Hz, however, the possibility of discriminating the interruption rate of chopped noise decreases in contrast with the band-filtered periodic pulsetrain. So there is a discrepancy between both for higher repetition frequencies. The discrimination of the interruption rate of chopped noise must be based on temporal aspects, because the noise lacks any

spectral information. Even the short-term spectrum may be considered white in our case (Pierce et al., 1977).
The jnd's in rattle rate are in agreement with the literature (Miller and Taylor, 1948; Mowbray et al., 1956; Wicke and Houtsma, 1975). The results for the chopped noise can be described in terms of the low-pass filter characteristic of the auditory system as far as envelope detection is concerned (Terhardt, 1967; Rodenburg, 1972; Green, 1973; Buunen, 1976). Others have reported accurate matches up to still higher repetition frequencies: Harris (1963) up to 750 Hz and Pollack (1969) even up to 2000 Hz for one subject. This might be related to the results found for the bandfiltered periodic pulsetrain with $n > 20$ in our case.
For very low frequencies, say below 50 Hz, both the rapidity of the noise bursts and the clicks of the pulsetrain are more prominent than a sensation of pitch. Subjectively, the observers reported indeed that they tried to compare the rapidity of the click or burst rates in their discrimination task. For higher repetition frequencies this sensation changes gradually in such a way that some pitch assignment in the sense of rank ordering on a low-high scale can be made (Flanagan and Guttman, 1960). This is more pronounced for the pulsetrain than for the chopped noise. This pitch, called "rattle pitch" by Plomp (1976), is probably not a pitch in the sense of low pitch, though melodies can be played with it and recognised (Burns and Viemeister, 1976). It seems rather that the roughness or harshness of the stimulus gives some ordering cue. Extrapolating from the coincidence of the jnd_g's at low repetition frequencies, discrimination on temporal features should also apply to the periodic pulsetrain. Above 100 Hz a divergence can be observed (fig. 3.3). In the case of the periodic pulsetrain it is surprising for what high repetition frequencies (400 Hz at f = 10 kHz) the relative jnd_g remains constant. Perhaps differences in correlation between successive noise bursts on the one hand and between successive pulses on the other play a part. This would tell in favour of an autocorrelation detector (Patterson and Johnson-Davies, 1977). We may say with good reason that bandfiltered periodic pulsetrains with $n > 20$ do not possess significant spectral information for the ear to use for frequency discrimination.

For $n < 20$ spectral information due to the resolving power of the ear apparently becomes available on which better frequency discrimination is possible. The relative jnd_g decreases

according as the frequency components are better resolved, until the harmonics are completely separated by the ear, whereupon the relative jnd_g remains constant. Qualitatively the obtained frequency discrimination curve is in agreement with our starting point, that frequency discrimination of complex tones depends on the frequency analyzing capacity of the auditory system. In section 3.6 the relation will be examined more quantitatively.
The course of the frequency discrimination curve might have other explanations, without relying on the frequency analyzing capacity of the ear. In a frequency discrimination experiment the observer can make use of any cue available. Introspectively discrimination takes place on the pitch of the fundamental. The pitches of the individual harmonics may also have been used. Timbre changes and amplitude variations of the harmonics, particularly those on the skirts of the filter, may have served as a discrimination cue. We do not know for certain which cue has been used, but we suppose that the observers were sufficiently trained to use that cue which yields the smallest jnd_g-values. In the next sections we will deal with these various discrimination cues.

3.3 Influence of the filter characteristic

In the previous section it appeared that the relative jnd_g is a characteristic function of the repetition frequency g for a given filter frequency f. This function is rather similar for all filter frequencies. To what extent this characteristic function depends on the filter characteristic will be examined in this section. Two parameters determine the filter characteristic in the frequency domain, viz. the bandwidth and the attenuation rate outside the passband. The phase characteristic will be left out of consideration because differences in phase relationship between the harmonics of a complex tone do not influence frequency discrimination essentially. We will consider first the effect of the filterbandwidth and subsequently the effect of the slope steepness on the frequency discrimination of the repetition frequency.

The bandwidth of the filter used in the previous section was 1/3-octave. This implies that especially at relatively high repetition frequencies only a few harmonics will fall within the passband of the filter. Considering this, it is hardly surprising that for $n < 8$ the relative jnd_g equals the relative jnd_f: only one harmonic is situated within the passband. Therefore it is desirable to investigate the importance of the number of components within the passband. The frequency discrimination measurements were repeated with the AX-method at f = 2 kHz with the bandwidth widened to one full octave. The results, obtained from four subjects at 40 dB SL, were essentially the same for the octave and 1/3-octave conditions. The lower cut-off frequencies coincide for the octave filter at 2 kHz and the 1/3-octave filter at 1.6 kHz. Within measuring error it could not be decided whether the results in the octave condition were best comparable to the discrimination results for a 1/3-octave wide filter centred at f = 1.6 kHz or at 2 kHz, though a slight tendency could be observed towards a better correspondence with the 1.6 kHz filter configuration.

The influence of the attenuation rate outside the passband will be examined more extensively in the following. Because the bandfilter used in section 3.2 has a finite attenuation rate outside the passband (this will be called slope steepness), changing the repetition frequency, the harmonics situated on the skirts of the filter undergo together with a frequency shift also an amplitude change. With a positive frequency shift the amplitudes will rise on the low-frequency skirt, whereas they fall on the high-frequency skirt. These amplitude changes become larger with increasing slope steepness and may have been used by the observers as a cue for discriminating the two stimuli of a pair. An extreme case is reached when the slope becomes infinitely steep. A change in the repetition frequency produces at the same time an apparent shift in the filter frequency. Provided that the number of harmonics within the passband does not change, frequency discrimination can be measured normally. Otherwise the discrimination would depend upon the exact relation between the lowest or highest harmonic and the lower or upper cut-off frequency of the filter respectively, because the falling out of one harmonic will be easily recognizable. The filter frequency can of course also be shifted indepently of the repetition frequency. According to the literature (Ritsma, 1968) changes of the filter frequency can very well be discriminated when the repetition frequency is kept constant. The discrimination accuracy appears to be independent of the repetition frequency itself, and is mainly determined by the slope steepness of the filter.

Using again the AX-method the jnd_g was measured as a function of g for filter configurations with a filter frequency of 2 kHz, a bandwidth equal to 1/3-octave and with various slope steepnesses. The values of slope steepness used were: 50, 100, 150, 200 and ∞dB/oct approximately. Up to and including 200 dB/oct analogue filters were used. The condition with slope steepness ∞dB/oct was realised by means of the digital computer.

The waveform resulting from the addition of the waveform of a number of harmonics of equal amplitude was calculated at regular intervals within one period. This sampled waveform could at a desired rate be transformed by digital-to-analogue conversion into voltage changes. Low-pass filtering removed all aliasing products afterwards. The signal thus obtained simulated the impulse response of a rectangular filter.

The stimuli were presented diotically to the observers at 40 dB SL for the 100, 150 and 200 dB/oct filters and also for the simulated filter. For the 50 dB/oct filter a SL of 30 dB was used. The lower sensation level was chosen to limit the stimulated frequency region. In the previous section it was described that changes in SL do not influence the results appreciably, provided that the S/N-ratio is kept at 40 dB. It was observed, however, that for the 50 dB/oct filter the results improved slightly when the SL increased from 30 to 40 dB. This is attributed to the fact that harmonics on the low frequency skirt of the filter become more important (see Ritsma, 1963).

Four observers participated in this experiment. The results are given in fig. 3.5 for all observers individually. Generally the symbols represent a single threshold determination. Apart from individual differences it can be seen that the frequency discrimination curve does not alter essentially when the filter slope steepness increases from 50 dB/oct to 150 dB/oct. With the 200 dB/oct filter this tendency is still there, but a number of deviating data points is found too, especially in the frequency region from 100 to 140 Hz. The relative jnd_g is considerably smaller for some of these frequencies, but not for all and depending upon the observer. Precursors of these drops may be seen incidentally among the data points belonging to other filter selectivities. Quite a contrasting behaviour is found in the case in which the skirts of the filter were omitted completely. For repetition frequencies below 200 Hz the relative jnd_g has a constant value slightly above 0.001, i.e. roughly twice the pure tone

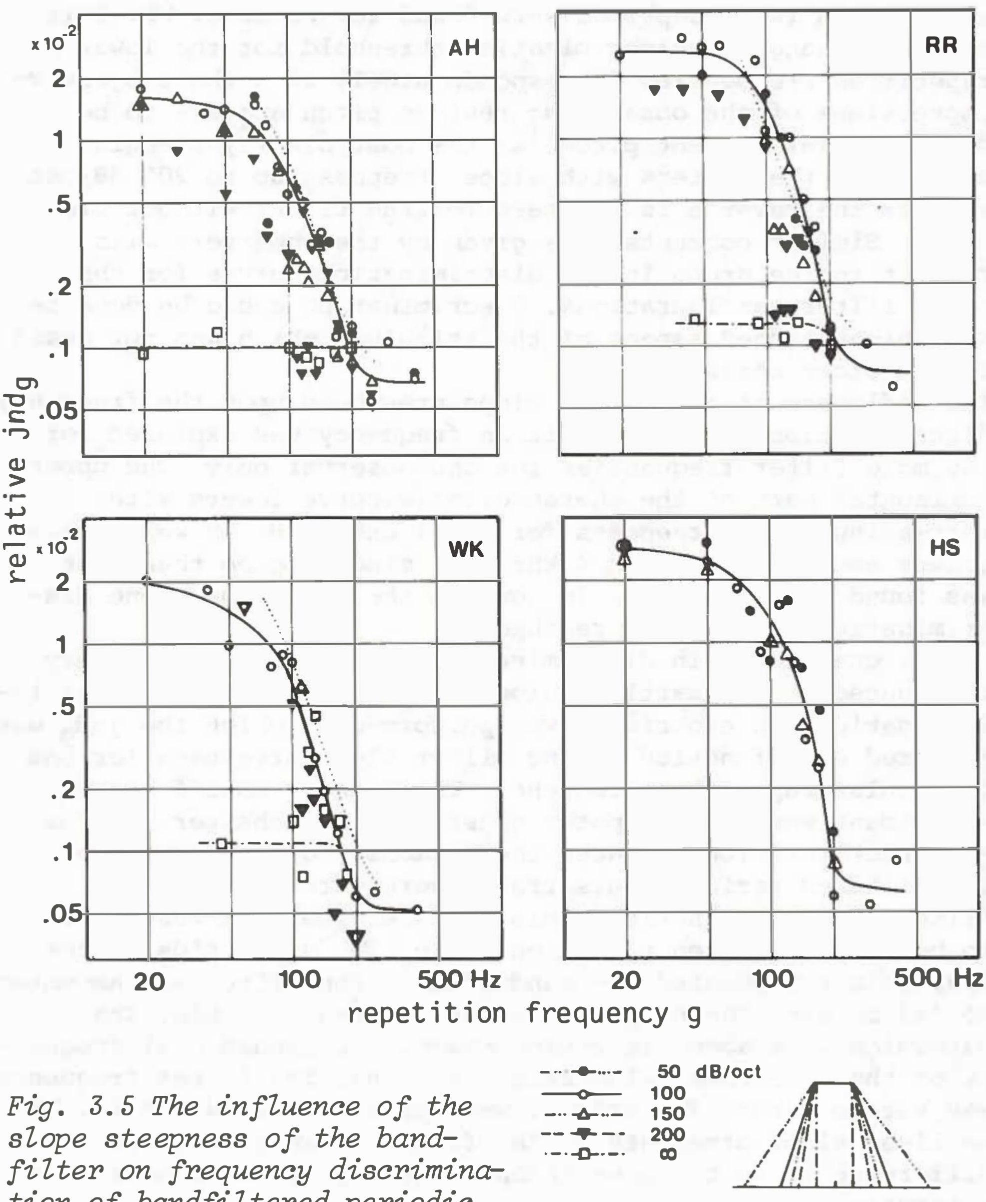


Fig. 3.5 The influence of the slope steepness of the bandfilter on frequency discrimination of bandfiltered periodic pulsetrains. The data of 4 observers have been plotted individually. The dotted lines represent the calculated relative jnd_g's (see section 3.4).

accuracy. A few exceptions were found for observer WK. This striking change in discrimination threshold for the lower repetition frequencies corresponds nicely with the subjective impressions of the observers: residue pitch appears to be dominant over formant pitch[1] as the most clearly changing aspect for the filters with slope steepness up to 200 dB/oct, whereas the reverse is the case for the filter without side-bands. Similar comments were given by the observers with respect to the drops in the discrimination curves for the other filter configurations. Discrimination could be done on some high-pitched aspect of the stimulus, which was not heard in the other cases.

The influence of the filter slope steepness upon the frequency discrimination of the repetition frequency was explored for two more filter frequencies for one observer only. The upper horizontal part of the characteristic curve lowers with increasing slope steepness for f = 1 and 4 kHz as well. This occurs especially at f = 4 kHz to a minor degree than what was found for f = 2 kHz. In none of the cases pure tone discrimination accuracy is reached.

The changeover in discriminative behaviour which is very pronounced in the rattle region, was subjected to a closer investigation. An experiment was performed in which the jnd_g was measured as a function of the filter slope steepness for one particular repetition frequency. The signals used for this experiment were all computer generated (see chapter 2). The amplitude relations between the harmonics of the simulated bandfiltered periodic pulsetrains were determined by the filter transfer function. This transfer function was chosen to be trapezoidal on a log-log scale. The upper side of the trapezoid represented the bandwidth of the filter and amounted to 1/3-octave. The slope of the skirts was variable. The harmonics were added in cosine phase. The fundamental frequency of the reference pulsetrain was 50 Hz. The filter frequency was set to 2 kHz. The stimuli were presented at 40 dB SL. The smallest slope steepness of the filter at which a fixed difference Δg in the repetition frequency could be heard was determined.

The data for one observer are given in fig. 3.6. A gradual transition can be seen from very good frequency discrimination

1) *Formant pitch is a pitch associated with the peak in the spectral envelope of a sound.*

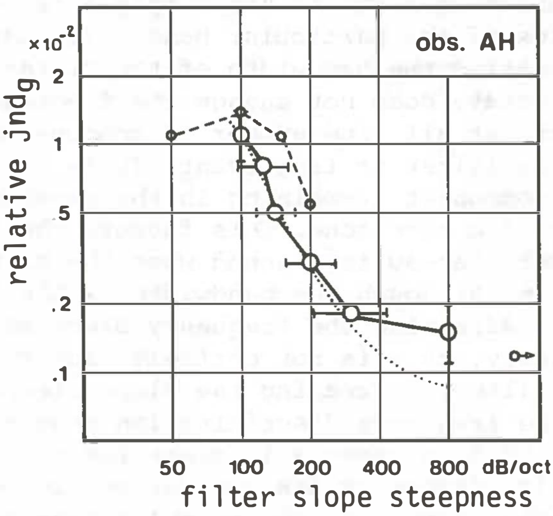


Fig. 3.6 The jnd in repetition frequency of a pulse train with low repetition frequency as a function of the slope steepness of the bandfilter. Data of one observer. The filter envelope was trapezoidal on a dB-log f scale. Small symbols are data taken from fig. 3.5a. The dotted line was calculated on the assumption that only one frequency component determined the discrimination threshold (see section 3.4).

at the higher filter slope steepnesses (> 300 dB/oct) to much worse discrimination with the less selective filters (< 100 dB/oct). This is not conflicting with the results from fig. 3.5. The results at g = 50 Hz may be considered as representative of other repetition frequencies in the rattle region.

Summing up, it appears that the characteristic frequency discrimination curve found in section 3.2 is not affected appreciably by changing the filter slope steepness between 50 and 150 dB/oct, which means that it is unlikely that amplitude variations of particular frequency components determine the jndg. Increasing the slope steepness beyond a certain value, however, disturbs the curve, eventually yielding a nearly flat curve for extremely selective filters.

Discussion

The results presented in this section show clearly that the

frequency discrimination curve is not simply a reflection of the characteristics of the particular bandfilter used in section 3.2. Increasing the bandwidth of the filter from 1/3-octave to a full octave does not change the frequency discrimination results at all. The number of components within the passband of the filter is irrelevant. It is not necessary to have only one component remaining in the passband to reach the relative jnd_f of a pure tone. This favours the interpretation that the lower plateau is reached when the harmonics are resolved completely. Although the bandwidth of the filter may be changed without affecting the frequency discrimination results substantially, this is not entirely true for the slope steepness of the filter. Increasing the slope steepness beyond about 150 dB/oct the frequency discrimination results grow better for $n > 10$. This is especially clear for the upper plateau. Apparently, frequency discrimination can be done more profitably on another aspect of the stimulus than on the periodicity of the waveform envelope for extreme steep filter slopes.
For increasing filterslope steepness timbre changes, accompanying the changes in repetition frequency, are easier to perceive than the changes in repetition frequency. The jnd_g's measured cannot be explained by shifts in the centre of gravity of the frequency spectrum along the frequency axis (timbre is in a first approximation associated with the centre of gravity of the frequency spectrum (see Plomp, 1976)). For the slope steepnesses involved these shifts are smaller than the shifts in the frequencies of the components, except in the condition with an infinitely steep filterslope. For low repetition frequencies such as g = 50 Hz no perceptible shifts in the centre of gravity occur for slope steepnesses below about 1600 dB/oct. We have to look for another explanation. As the filter does not actually shift but only the frequency components, the increase in the relative jnd for decreasing filterslope might be attributable to the fact that the frequency shift of the components in the passband of the filter is gradually masked by the rising components on the low-frequency skirt of the filter. A shift in frequency would be heard easier when the neighbouring lower harmonic is of a lower level. The discrimination accuracy would than be inversely proportional to the degree of masking of a particular frequency component. Assuming this proportionality the results of 3.6 can qualitatively be explained. The same reasoning applied to other repetition fre-

quencies would predict smaller jnd_g's with increasing slope steepness of the filter and accordingly a shift in the sloping part of the frequency discrimination curve towards lower g with increasing slope steepness. Looking at fig. 3.5 there is no shift to speak of. The only thing to be noticed is that at some repetition frequencies which vary from observer to observer, the relative jnd_g is exceptionally small. The individual disparity as to the frequencies at which this occurs make a physical cause less probable. It is interesting that the observers for these very repetition frequencies report to discriminate on "something high". It is not clear why such analytical hearing occurs in some cases, while at other nearby repetition frequencies the complex tone is heard as a whole and discrimination takes place introspectively on pitch.

From the above it may be concluded that neither shifts in the centre of gravity of the signal spectrum nor changes in the levels of the components in the filter skirts are of real importance for the frequency discrimination results reported in this section. Changes in the degree of masking of a particular harmonic by its low-frequency neighbour can explain only a part of the results.

3.4 The influence of added noise

It is well known that the accuracy with which the frequency of a pure tone can be discriminated declines with decreasing sensation level (e.g. Harris, 1952). The same is valid for low signal-to-noise (S/N) levels when the pure tone is presented against a noise background (Cardozo, 1974). A similar finding was reported by Campbell (1963) for a pulsed sinusoid. Apart from this isolated observation no data about frequency discrimination of complex tones in noise are known to the present author, so that it seemed worthwhile to investigate frequency discrimination of bandfiltered periodic pulse trains for low S/N-ratios. It gives another possibility to check the assumption that complex tones can be discriminated as well as pure tones only when their frequency components are resolvable.

For the whole range of repetition frequencies covered in the previous section the jnd for frequency was determined as a function of the S/N-ratio. The added noise was filtered through the same 1/3-octave bandpass filter (B & K 1615, slope steepness 100 dB/oct) as the pulse train. The noise was generated by a maximum length sequence generator and presented only simultaneously with the pulsetrains. This synchronous presentation of noise and signal provided always the same background for every stimulus. The noise can be conceived as a part of the signal, be it a disturbing one. The apparatus used has been described in chapter 2 (section 2.1, fig. 2.2 and 2.3). The pulsetrains were presented at 40 dB SL. First the noise level required to mask the pulsetrain, was determined with the AX-method as described in section 2.2. In this detection experiment the observer had to indicate which of two identical noise bursts contained the signal. The detection threshold could be established with an error of about 2 dB, averaged over different sessions on different days. Different amounts of noise were needed to mask pulsetrains with different repetition frequency but the same sensation level. The measured noise levels were generally in agreement with the expected values: a 3 dB decrease in noise level for every halving of the repetition frequency. The results for different repetition frequencies were normalised to each other, in accordance with this regression. For every repetition frequency the signal-to-noise ratio was therefore expressed in dB attenuation of the noise, relative to the (normalised) level of the noise required to mask this particular pulse train presented at 40 dB SL.

Frequency discrimination measurements were carried out in two different ways: for large S/N-ratios the jnd_g was determined by varying Δg, for small S/N-ratios it was advantageous for easier measuring to vary the S/N-ratio keeping Δg constant. For intermediate S/N-ratios both strategies were used and they yielded the same results. A variable S/N-ratio was as a rule only used for $\Delta g/g$-values larger than four times the relative jnd_g achieved without masking noise. The measuring method was again the AX-method. Three observers participated in this experiment. Fig. 3.7 shows the individual data for a filter frequency of 2 kHz. Standard deviations were typically a factor 1.4 when Δg was variable and one or two dB when the S/N-ratio was variable. From fig. 3.7 it can be seen that the smallest jnd_g values are obtained for S/N-ratios above about 20 dB irrespective of the repetition frequency. For S/N < 20 dB the relative jnd_g increases with decreasing S/N-ratio. The rate of decrease depends on the harmonic number $n = f/g$. The results can be divided in two groups: one for low and one for high harmonic numbers. The transition occurs roughly at n = 14, but is somewhat subject dependent. Irregularities can be observed in figs.3.7b and 3.7c in this region. For the lower harmonic numbers ($n < 14$) the rate of decrease in discrimination accuracy for the bandfiltered periodic pulsetrain is comparable to that of the pure tone and roughly equal to a factor 2 per 3 dB. For the higher harmonic numbers ($n > 14$) the decline in discrimination accuracy is different. There seems to be a minimum S/N-ratio below which discrimination is not possible, at least if the differences do not exceed 10 per cent.

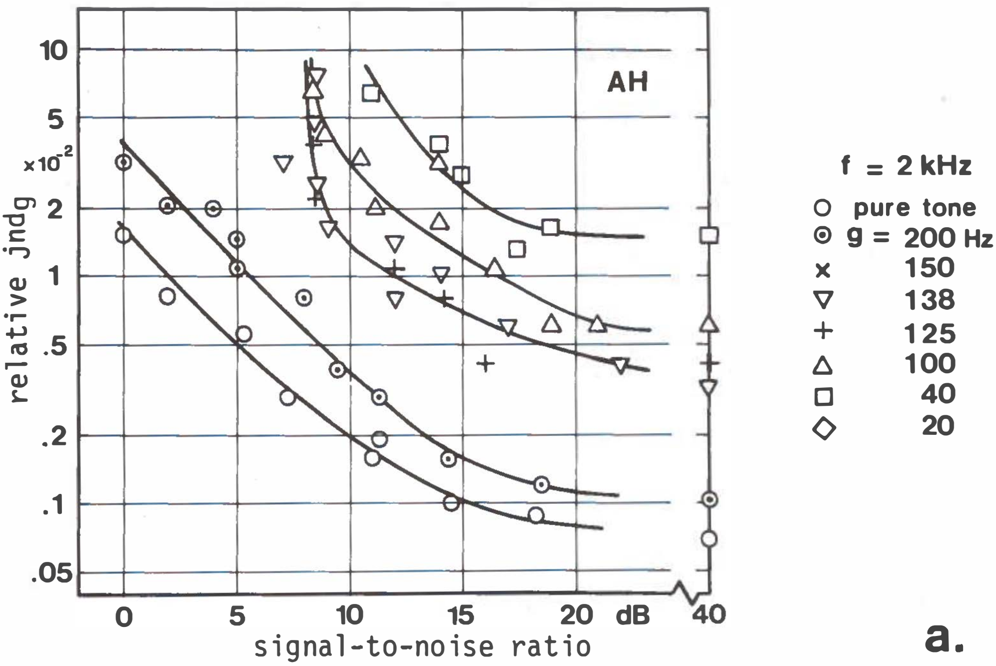
The subjective impressions evoked by the stimuli are in agreement with this bifurcation. For S/N > 10 dB, the stimuli sound as a noise with a more or less contrasting signal. For S/N < 10 dB the signal fuses with the noise. For complex tones consisting of low harmonics the signal manifests itself then by a colouration of the noise. Frequency discrimination is possible upon this colouration. For complexes with only high harmonics only a grumbling superimposed on the noise betrays the presence of a signal. Discrimination upon this grumble appears to be impossible.

To quantify these subjective impressions the observers were asked to adjust the noise level in such a way that the signal just fused with the noise or just stood out against the noise. The adjusted noise levels varied between S/N = 5 dB and S/N = 9 dB, depending on the in- or decreasing of the noise level, in other words, depending on the initial audibility or inaudibility of the signal. The results were fairly independent of the repetition frequency. From this it can be concluded that for the low repetition frequencies, the signal should be clearly outlined against the noise in order to make frequency discrimination possible.

No frequency differences exceeding 12% were used to explore the asymptotic behaviour further because then the observers become aware of loudness differences[1)] upon which discrimination is possible. The discrimination task then differs from the initial one.

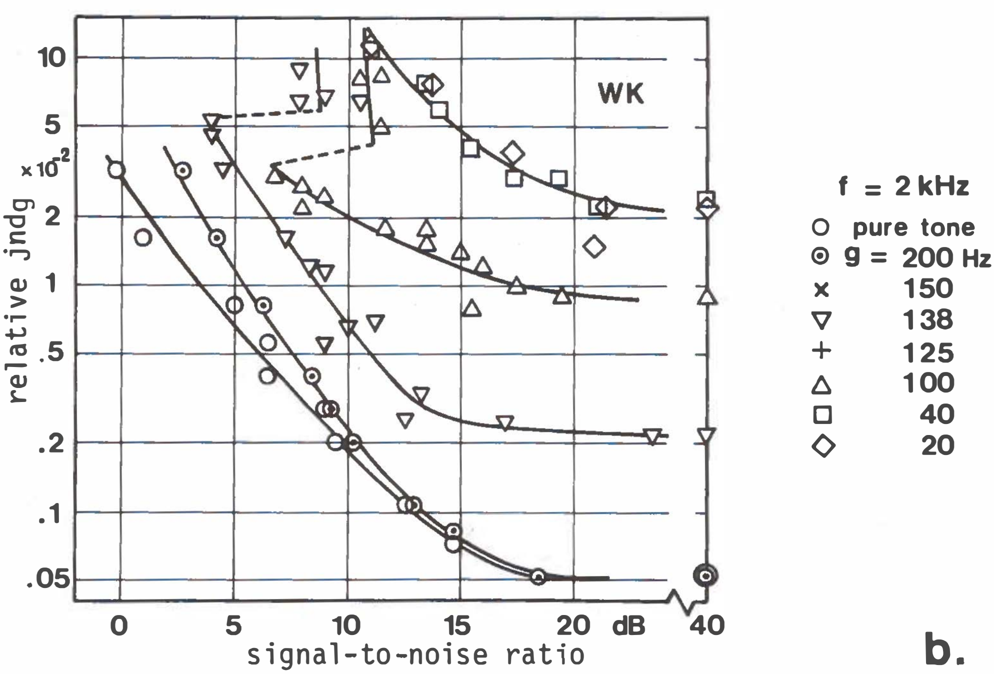
Irregularities in the curves can be observed in fig. 3.7b for g = 138 Hz and g = 100 Hz and in fig. 3.7c for g = 138 Hz. Observer RR was able to penetrate the barrier at S/N = 10 dB a few times. The standard deviation in these instances was

1) *With increasing pulse rate the loudness grows when the pulse strength is kept constant.*



AH
relative jndg ×10⁻²
10
5
2
1
.5
.2
.1
.05
0
5
10
15
20
dB
40
signal-to-noise ratio
f = 2 kHz
pure tone
g = 200 Hz
150
138
125
100
40
20

a.



WK
relative jndg ×10⁻²
10
5
2
1
.5
.2
.1
.05
0
5
10
15
20
dB
40
signal-to-noise ratio
f = 2 kHz
pure tone
g = 200 Hz
150
138
125
100
40
20

b.

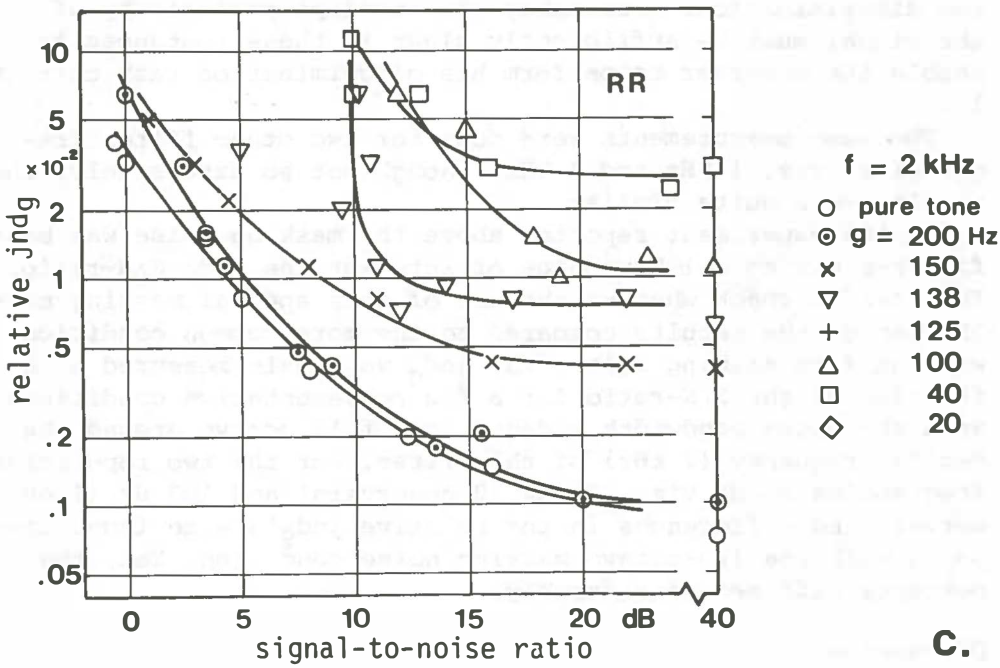


Fig. 3.7 Frequency discrimination as a function of the signal-to-noise ratio. Individual data of 3 observers. The masking noise was bandfiltered through the same 1/3-octave filter as the periodic pulse train. A clear division of the curves in two groups can be seen.

exceptionally large due to the fact that once the discrimination cue is lost, the S/N-ratio has to be increased at least up to 10 dB before this cue can be found again. Measurements in this region are extremely difficult. For observer WK the irregularities are of a different kind. Although the same measuring difficulties mentioned above were encountered he is able even for g = 100 Hz, to penetrate the barrier up to a Δg~3 Hz. For larger Δg about 4 dB better S/N-ratio is required for correct discrimination, bringing him again in the region where the signal can be heard in clear contrast with the noise. At the discontinuity Δg is so large in both cases (g = 100 Hz and 138 Hz) that the spectra of the stimuli are nearly identical, viz. the n^{th} harmonic of the fundamental g has approximately the same frequency as the $(n - 1)^{th}$ harmonic of the fundamental $(g + \Delta g)$ in the frequency region important for the discrimination. Presumably the envelope periodicity of the signal must be sufficiently clear in these instances to enable the observer to perform his discrimination task correctly.

The same measurements were done for two other filter frequencies, viz. 1 kHz and 4 kHz, though not so extensively. The results were quite similar.

In the experiment reported above the masking noise was bandfiltered giving all harmonics of interest the same S/N-ratio. In order to check whether the use of this special masking noise influences the results compared to the more common condition with uniform masking noise, the jnd_g was again measured as a function of the S/N-ratio for a few representative conditions with the noise bandwidth widened to a full octave around the centre frequency (2 kHz) of the filter. For the two repetition frequencies used, viz. 200 Hz (2 observers) and 100 Hz (1 observer), no differences in the relative jnd_g's were found compared with the 1/3-octave masking noise condition. Yet, the percepts differed considerably.

Discussion

The addition of noise to the bandfiltered periodic pulse train has accomplished a clear division of the data in two groups. This dichotomy supports the idea of the existence of two different mechanisms of frequency discrimination for low and high n as advanced in section 3.1. Frequency discrimination can be done fairly accurately for signals with low harmonic numbers. An accuracy of a few per cent is still possible at or near S/N = 0 dB (dectection threshold), just as for a pure tone. For pure tones this was earlier reported by Cardozo (1974). The jnd_f's for the pure tone as a function of the S/N-ratio are in agreement with the literature (Harris, 1966; Cardozo, 1974). For signals with high harmonic numbers, on the other hand, at least 10 dB S/N-ratio is required for correct discrimination. The separation between both groups is roughly at n = 14, although a slight subject dependence is found. This harmonic number is a little lower than the transition point (n = 20) which was found is section 3.2. The addition of noise disturbs probably some discrimination cue, which is felt most strongly for those signals having only weak discrimination cues apart from envelope periodicity. The boundary at S/N = 10 dB may be related to the minimum modulation depth required in envelope

detection.
Taking into account the subjective impressions which show a transition region between 5 and 9 dB S/N-ratio from coloured noise to noise plus a contrasting signal, it is acceptable to suppose that a slight indication of envelope periodicity is needed to give the signal a clear identity. Although the envelope periodicity by itself does not give a complex tone a distinct pitch, it may facilitate the assigning of the correct pitch to a group of harmonics. The irregularities in the curves for g = 138 Hz and 100 Hz from fig. 3.7b and c support this view. If the spectral configurations of both stimuli are readily confused some envelope periodicity is apparently needed to obtain correct discrimination. This is manifest in a discontinuity in the curves. It occurs, of course, particularly for those conditions in which the limit of frequency resolution is approached.

Experiments by Bilsen (1973) concerning the discrimination of a pitch jump in two- and three-tone complexes in noise show that broadband noise masks a pitch jump of 6% of the fundamental frequency more easily for low than for high fundamental frequencies at the same central frequency. For the same fundamental frequency there seems to be some stabilisation in the required masking level beyond n = 14. This finding may be related to the asympotic behaviour of the frequency discrimination results at high harmonic numbers in our data, although we did not make pitch comparisons.

In the previous section it was suggested that the degree of masking of the lowest component in the passband of the filter might be of deciding importance for the achieved frequency discrimination accuracy. Based on the obtained frequency discrimination results of a pure tone in noise a prediction can be made of the relative jnd_g of the complex tones, starting from its physical frequency spectrum. The predicted frequency discrimination curve does not show the least correspondence with the curve from section 3.1. For high harmonic numbers a better frequency discrimination is predicted than what is measured.
A better correspondence is found between predicted and measured jnd_g as a function of the slope steepness in the rattle region (see fig. 3.6), when it is assumed that the discrimination accuracy is determined by the amplitude ratio of the lowest harmonic in the passband of the filter and its low-frequency neighbour. The relative jnd_g for a certain amplitude ratio is

taken to be equal to the relative jnd_f of a pure tone in noise at an equivalent signal-to-noise ratio.
The frequency discrimination results in noise of complex tones with low harmonic numbers and also the shape of the lower part of the characteristic frequency discrimination curve of section 3.2 may be linked quantitatively to the pure tone frequency discrimination results in noise by calculating for the complex tone the peak-to-valley ratio in its hypothetical excitation pattern for all harmonic numbers (Ritsma and Hoekstra, 1974 a,b). This excitation pattern is constructed by summation of the excitation patterns of the individual harmonics, which may be described by two straight lines on a dB-log f scale. This excitation pattern reflects the frequency selectivity of the peripheral auditory system. The peak-to-valley ratio may be considered to be a measure of the degree of frequency resolution of the complex tone. The peak-to-valley ratio becomes smaller with decreasing repetition frequency, i.e. with decreasing frequency separation between the components. A relative jnd_g can be assigned to any peak-to-valley ratio on the basis of the relative jnd_f of a pure tone in noise at an equivalent signal-to-noise ratio. In this way the calculated course of the lower part of the characteristic frequency discrimination curve can be fitted fairly well to the experimental data (see fig. 3.5). The fact that the experimental data can be fitted better on the basis of peak-to-valley ratios in the internal excitation pattern than on the basis of amplitude ratios in the physical amplitude spectrum supports in the authors opinion the hypothesis that frequency discrimination of comlex tones depends on the frequency analyzing capacity of the ear.

3.5 Non-overlapping spectra

In many of the foregoing experiments the observers reported retrospectively that they discriminated the two signals by comparing their pitches. It is by no means certain, however, that frequency discrimination of the repetition frequency of a band-filtered pulsetrain took place essentially upon pitch matching. Every other aspect of the complex sound may have been used for the discrimination task. The signals could be matched in all aspects. In order to find out to what extent the characteristic frequency discrimination curve found in section 3.2 depends on the possibility of such a perfect matching, the following experiment was performed. The jnd in repetition frequency was

measured for different repetition frequencies of bandfiltered periodic pulsetrains. The bandfilter was now set at different frequencies in both observation intervals. The 1/3-octave bandfilters used were separated by one octave. The repetition frequencies were randomized in the two observation intervals, but the setting of the filter frequencies was fixed: f_1 in the first interval, $f_2 = 2f_1$ in the second or vice versa. To avoid comparisons between consecutive stimulus pairs, the reference repetition frequency was slightly roving. This means that every stimulus pair had a somewhat different reference repetition frequency than its predecessor. The different reference repetition frequencies could be chosen out of three: g, $g + g^1$ and $g - g^1$. The choice was randomized in such a way that never the same reference frequency was used in successive stimulus pairs. The three frequencies were kept close together (g^1 ranging from g/100 for high g to g/10 for low g respectively), so that all data may be pooled. The only possible way to discriminate between two such stimuli is by comparing the pitches or the repetition rates of both pulsetrains. As the large timbre differences make the discrimination task more difficult, a training period was necessary. To obtain the jnd_g's the PEST-method was used in this experiment (see section 2.2). The whole experiment was under computer control. The stimuli were presented diotically at 40 dB SL. Two observers participated in this experiment. Data were collected extensively for one observer, while the other served as a check.
At first it was checked whether this new measuring method with roving reference signal did not influence the results when the same filter frequency was used in both observation intervals. The results were in this situation essentially the same as those obtained with the AX-method in section 3.2 (compare the figures 3.1 and 3.8). The absolute values of the jnd_g's were slightly larger here, probably due to the more difficult discrimination task. From fig. 3.8 it can also be seen that using different filter frequencies in the observation intervals, the characteristic frequency discrimination curve is preserved. For the combination: f_1 = 1 kHz and f_2 = 2 kHz (or vice versa: interchanging of f_1 and f_2 does not really matter as far as the discrimination threshold is concerned) a curve is found comparable to that for $f_1 = f_2$ = 2 kHz. The jnd_g's are about a factor two larger, though. This corresponds with findings of Ritsma (1965) for amplitude modulated pure tones. It seems as if the signal having the least pronounced pitch of the two

determines the discrimination threshold. The combination: f_1 = 2 kHz and f_2 = 4 kHz (or vice versa) yields similar data, also shown in fig. 3.8. Again the higher filtered signal limits the discrimination performance, so that now the curve is comparable to the one for $f_1 = f_2$ = 4 kHz. A few data were obtained for the combination: f_1 = 4 kHz and f_2 = 8 kHz. The spread in the data is considerable and it is no longer clear whether the characteristic curve still exists. The disappearance of the characteristic curve for this filter combination

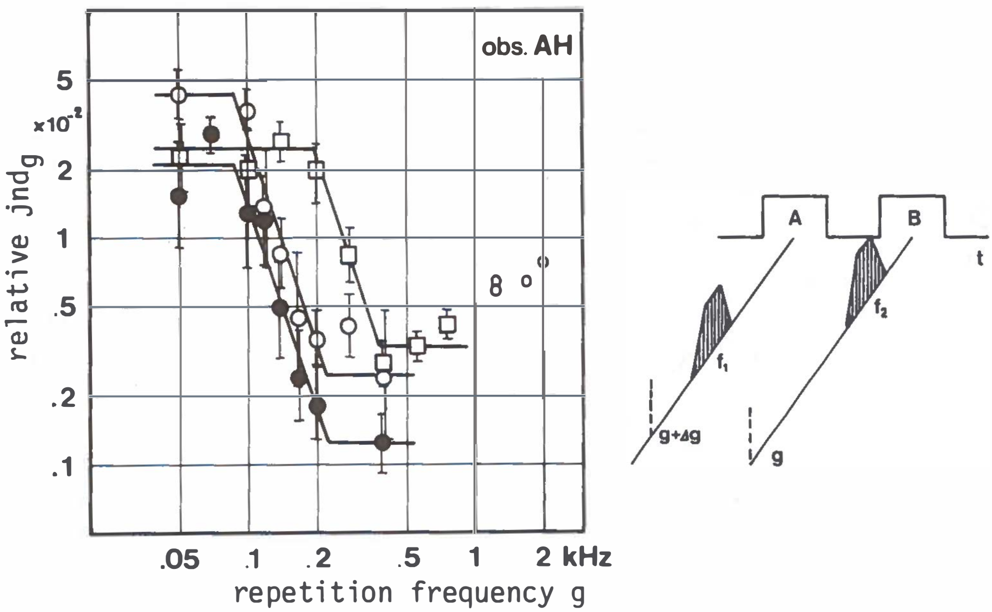


Fig. 3.8 Frequency discrimination data of one observer for non-overlapping spectra. The bandfilters were separated by one octave. (○: f_1 = 1 kHz, f_2 = 2 kHz; □ : f_1 = 2 kHz, f_2 = 4kHz). The closed symbols represent the data of the normal condition: $f_1 = f_2$ = 2 kHz. Small symbols show octave matching accuracy from the literature (Ward, 1954; Ritsma, 1965). The curves have been schematized by straight lines.

would be in agreement with the extent of the existence region of the tonal residue (Ritsma, 1962).

The curves of fig. 3.8 are truncated on the high frequency side at 400 Hz and 800 Hz respectively. Extending the curves to 1 kHz and 2 kHz respectively would lead to octave comparisons for the condition of non-overlapping spectra. Not

everyone is able to make octave matches and even for musically trained subjects octave matches are more difficult than pure tone matches (Ward, 1954; Ritsma, 1965). Octave matching data of these authors have been included in fig. 3.8; they would give the lower plateau an upward curvature.
Another notable aspect of this experiment is that it shows the possibility to equate a low pitch with a rattle pitch (g = 140 Hz and 200 Hz for the filter combination f_1 = 2 kHz / f_2 = 4 kHz).

Discussion

In the experimental condition of non-overlapping spectra discrimination of changes in the repetition frequency cannot occur by means of a comparison of the activity changes in the same neural channels. Different groups of nerve fibres are stimulated by the two signals. It is only after the fusion of information in a single common aspect such as periodicity or pitch that discrimination can take place. The data show the same dependence of the relative jnd_g on g as in the normal condition, i.e. the same filter frequency in both observation intervals. The discrimination score is not bound to a certain pitch or periodicity, but depends again on the ratio of filter- and repetition frequency. So we may discard envelope periodicity as the decisive discrimination cue, except of course in the rattle region. Pitch would do as a discrimination cue only when the salience of pitch is taken into account. In recent research on pitch perception accumulating evidence has been found for the fact that frequency resolution is essential for the perception of low pitch (see section 1.3). Complete frequency resolution of at least one of the components seems to be necessary for pitch in the sense of musical pitch. Pitch ordering is a simpler task, which can also be performed with signals having rattle pitch. It is well known that the salience of pitch decreases with increasing harmonic number of the components (further away from the dominant region). Pitch ordering becomes more difficult when pitch saliency decreases. We suppose that the salience of pitch depends on the degree to which the complex tone can be resolved spectrally. A finer discrimination is found when the resolved contrast is greater, i.e. when more neural channels carry independent information which may be used complementary. So the explanation of the frequency discrimination data in terms of salience of pitch would fit in with our starting hypothesis that frequency discrimination of complex tones depends on the frequency analyzing capacity of the peripheral auditory system.

The floor of the discrimination mechanism of non-overlapping spectra is in accordance with the literature (Ritsma, 1965). Although the pure tone could be thought of as the limiting case of the lower plateau of the frequency discrimination curve for overlapping spectra, the octave apparently does not fill this part for non-overlapping spectra. This supports our earlier idea that it is not just the remaining of one harmonic in the passband of the filter that determines the lower plateau. Low pitch is still perceived at n = 4, despite of the fact that the harmonic on the skirts of the filter are about 25 dB down.

3.6 General discussion

The experiments described in this chapter have mainly been performed to find out whether a relation exists between frequency discrimination of complex tones and the frequency analyzing capacity of the auditory system. The most salient feature found, is the existence of a very characteristic frequency discrimination curve when the relative jnd_g is plotted against g. This characteristic curve consists of two plateaus of constant discrimination level connected by a transition region. The existence of two different discrimination mechanisms may explain the shape of the curve. The mechanism determining the upper plateau is most likely working on the periodicity in the waveform envelope (possibly an autocorrelation detector) as was argued in section 3.2. The accuracy of this mechanism is surpassed by the other discrimination mechanism. This mechanism works best for $n < 8$. Beyond n = 8, in the transition region, its effectiveness becomes less, until finally ($n > 20$) the resulting increase in relative jnd_g is limited by the other mechanism.

Different descriptions have been tried in the previous sections in order to account for the observed discrimination accuracies under different conditions. The results as a whole are, however, best unified by the hypothesis that frequency discrimination depends on the frequency analyzing capacity of the auditory system. The best discrimination results are obtained for those conditions in which frequency components of the complex tone can be resolved completely ($n < 8$). Beyond $n = 8$ the frequency resolution becomes incomplete, resulting in less contrast in the excitation pattern of the complex tone. Accordingly there will be less differentiated information contained in the activity pattern of the stimulated neural channels. The resulting increase in relative jnd_g with increasing harmonic number is limited by the other mechanism. The activity patterns in the various neural channels will now be nearly equal.

As noted before, the frequency discrimination task is performed subjectively upon pitch. It is then interesting to examine whether there are correspondences between pitch perception and frequency discrimination data. For the pitch of complex tones many different names have been used in the past, e.g. residue pitch, repetition pitch, virtual pitch, low pitch etc. Whether these terms refer really to different kinds of pitch and if so, which term should be used under what condition, is not clear. The transition from sounds which have a clearly defined pitch to sounds lacking this aspect is rather vague. This is especially the case at low repetition frequencies where additionally something like rattle pitch has to be distinguished. Rattle pitch corresponds to the periodicity of the waveform envelope and is closely connected with the sensation of roughness. Pitch ordering and interval recognition can be performed with both low pitch and rattle pitch. Although even melodies may be recognized when conveyed by variation in the modulation frequency of AM-noise (Burns and Viemeister, 1976), there is a considerable difference in the salience of both types of pitch. Can this be recovered in the frequency discrimination data? Three authors have measured what is called the existence region of residue pitch. Though their methods to arrive at the existence region differed, the results are remarkably similar (Ritsma, 1962; Walliser, 1968; Moore, 1973). In spite of its vagueness the perceptual attribute low pitch appears to be quite manageable. The results presented in fig. 3.3 are not at variance with the boundaries of the existence region. For the lower filter frequencies all complex tones which fall in the existence region have a relative jnd_g smaller than the relative jnd_g of the upper plateau. The existence region of residue pitch is smaller when LP-filtered noise is added to complex tones verging on the low frequency

side (Moore, 1973). This might correspond with the separation of the discrimination results in two groups at a lower n value when noise is added to the periodic pulsetrain as was found in section 3.3. One could argue that the characteristic frequency discrimination curve is explainable in terms of pitch saliency. This would defer the question about the discrimination mechanism to the mechanism of pitch extraction. It seems at present that in order to have low pitch, good frequency resolution as well as temporal resolution is required (e.g. the dominance region at about n = 5). So even then we can stil hold the frequency discrimination curve to express the limited frequency resolution of the auditory system.
The concept of frequency discrimination related to pitch saliency seems to fail for the higher filter frequencies: at f = 6.3 kHz a normal curve is still found (see fig. 3.3).

The fact that the slope steepness of the filter is not completely irrelevant for the frequency discrimination scores may seem to be in conflict with the hypothesis that frequency discrimination depends on frequency analysis. The relative jnd_g decreases with increasing slope steepness. It must be realised, however, that frequency analysis is not measured directly. In a discrimination task that aspect which gives the clearest distinction is used by the observer, neglecting other aspects. For very steep filters an "edge pitch"[1)] becomes more prominent. Discrimination is then more profitably done on this pitch than on the low pitch the signal undeniably still has. This overriding is especially clear in the rattle region. Apparently this "edge pitch" shifts with the frequency of the lowest harmonic in the passband of the filter with extreme steep slopes. It is then not surprising that the discrimination accuracy does not depend on the repetition frequency. One might even argue that with increasing slope steepness of the external filter at some point the slope steepness of the auditory filter is surpassed. In this sense also the results of fig. 3.6 reflect the limited frequency resolution of the auditory system. This possibility is further investigated in section 4.2.
From these results it follows that the frequency discrimination data do not always give an indication of the degree to

[1)] *By edge pitch we understand a pitch associated with a sharp cut-off in the frequency spectrum of a sound.*

which the complex tone has been resolved. Shifts of the centre of gravity of the complex tone along the frequency axis produce timbre changes which make frequency discrimination easier. For bandfilters with less steep slopes the presence of harmonics on the skirt compensates for the shift of the components in the passband, so that the centre of gravity does not change appreciably. Only then the characteristic frequency discrimination curve appears.

As the experiments described thusfar do not disprove our working hypothesis that frequency discrimination of bandfiltered periodic pulse trains depends on the frequency analyzing capacity of the auditory system, it may be asked whether a measure of the frequency analyzing capacity can be derived from the data. It is not an easy matter fo find an equivalent filter bandwidth of the auditory filter from the shape of the characteristic frequency discrimination curve without a suitable theoretical model. Taking the frequency separation of the harmonics at the upper bend as a measure would lead to a rather small bandwidth as compared to other data, even if it is taken into account that the lower harmonics are most important. The results of section 3.4 point to a minimal separation between the harmonics of about 140 Hz at 2 kHz. This is roughly the repetition frequency at the inflexion point of the characteristic curve, halfway between the two plateaus. This value is in agreement with some of the data in the literature(Evans and Wilson, 1973; Houtgast, 1974). The effective lowest harmonic would be about the 12th, not counting possible combination tones. Finally, the position of the lower bend might be used as a measure for the complete resolution of at least one of the harmonics. This harmonic should be separately audible. From the data we arrive at the 6th or 7th harmonic. This is fairly well in agreement with the literature (Plomp, 1964; Moore, 1973).

3.7 Untrained observers; frequency discrimination as a screening test

From the experiments of the previous sections it was concluded that the characteristic frequency discrimination curve is for a major part determined by the limited frequency analyzing capacity of the ear. Without having an exact delineation of the limit of the frequency analyzing capacity from our data,the curve as a whole and in particular its position against the n-axis could provide a basis for distinguishing between normal and abnormal frequency analysis. Before proceeding to measure the frequency discrimination capabilities of hearing impaired listeners it is worthwhile to determine the variations in the location of the curve for untrained, normal hearing listeners. For time-saving purposes it was decided to determine the location of the lower bend in the curve, assuming that the variation in the position of this bend is representative for the variation in location of the curve as a whole. The slope of the characteristic frequency discrimination curve was assumed to be constant in first approximation. The upper bend in the curve seemed less fit to fixate the position of the curve because of the larger measuring error among the trained observers in this region.

A short measuring procedure was devised. The test, applied to a large group of normal hearing listeners, consisted of a double threshold determination (fig. 3.9). In this way the in-

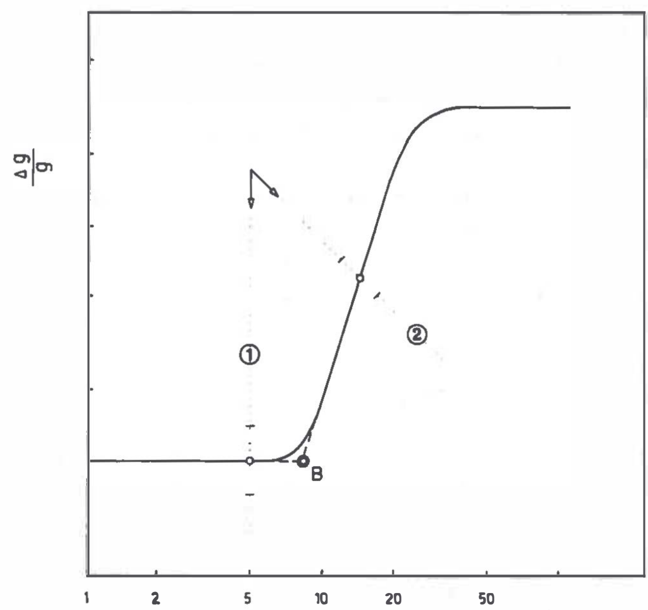


Fig. 3.9 Graphical representation of the test procedure to find the location of the characteristic frequency discrimination curve. The two courses of threshold determination are represented by dotted lines labelled 1 and 2. Dashed lines show the determination of the lower bending point B.

fluence of the performance level of the untrained observers is minimized. First the jnd_g of a bandfiltered periodic pulse train is determined for a constant reference repetition frequency at n = 5. Next a cross-sectioning in the sloping part of the curve is made by varying both the reference repetition frequency g and Δg in a prescribed way: g reference is decreased with decreasing Δg. When Δg is halved the reference repetition frequency was halved in most instances, but other ratios were used as well. Again a jnd_g is obtained but from a different angle of incidence. The actual Δg-values used in the cross sectioning were chosen in relation to the threshold value of the first measurement. In this way there result two differential thresholds from which the location of the lower bend in the characteristic curve can be obtained graphically by drawing two straight lines: one horizontal and one at an angle equal to that of the sloping part of the characteristic curve. This slope was taken to be equal to a factor 10/octave, based on the measurements with the trained listeners.
The AX-method was used to determine the jnd_g's. The bandfilter was the same as used in section 3.2. Subjects had to decide whether two consecutive stimuli were "equal" or "unequal". Visual feedback followed immmediately after the responses. In this way the effects of training within one session were minimised. The stimuli were presented diotically at 40 dB SL. With this testprocedure the location of the lower bend in the characteristic curve was determined for 52 untrained subjects with normal hearing, mainly medical students.
The results of these measurements are shown in fig. 3.10 in the form of histograms. Most measurements were carried out at f = 2 kHz and the histogram is clearly peaked. The mean frequency of the location of the lower bend for this filter frequency equals 217 Hz with standard deviation of 30 Hz,corresponding to n = 9 ± 1. Similar results were obtained for f = 1 kHz and f = 4 kHz though with fewer subjects. So the average location of the lower bend of the characteristic curve can be fixed at n = 9 ± 1.

For 20 untrained listeners the discrimination threshold in the rattle region was additionally determined. The mean jnd_g was found to be 0.05 with a standard devation of a factor 2.5.

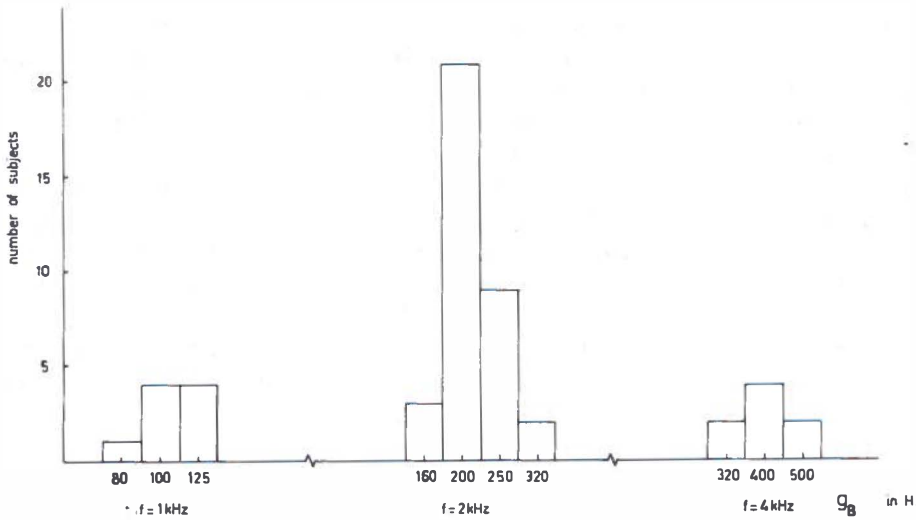


Fig. 3.10 Results of the determination of the lower bending point with the testprocedure for 52 untrained, normal hearing subjects shown as histograms.

Discussion

For untrained normal hearing observers the location of the characteristic frequency discrimination curve with respect to the n-axis can be determined in a relatively short time. The final result of the test procedure is fairly independent of the achieved "pure tone" frequency discrimination. Most observers discriminate either good or bad in both measurements. Moreover, the variation in the bendlocation is rather small. These findings make the test procedure suitable as a screening test for frequency discrimination, which might be applied to hearing impaired listeners to assess their frequency analyzing capacities.

CHAPTER 4

THE ROLE OF COMBINATION TONES

4.1 The influence of combination tones on frequency discrimination

When two pure tones sound together combination tones (CT's) will be produced under certain conditions (e.g. Goldstein, 1967). Even at low levels these distortion products may be produced by the ear. These CT's belong to a distinct class and their frequencies are given by $f_1 - n.(f_2 - f_1)$, with n being a small positive integer and f_1 and f_2 ($f_1 < f_2$) indicating the frequencies of the primary pure tones from which they originate. They are audible in a restricted frequency region below f . The audibility region depends on frequency and level of the primary tones (Smoorenburg, 1972a). The level of the combination tones decreases with increasing frequency difference between primaries of equal level. Combination tones may extend the frequency spectrum of a complex tone consisting of a group of higher harmonics considerably downwards.
In the previous chapter it was found that frequency resolution is an important factor in frequency discrimination of complex tones. The lowest harmonics of a complex tone are best resolved. Moreover, combination tones have been shown to be important for pitch perception of complex tones consisting of only a group of higher harmonics (Smoorenburg, 1970). As in our experiments frequency discrimination is at least subjectively based on a pitch comparison, there are two reasons why combination tones could be relevant for frequency discrimination.

The experiments described in this section pertain to the question of the relative importance of combination tones for frequency discrimination of complex tones. Jnd_g's in repetition frequency of bandfiltered periodic pulse trains are determined when noise is added on the low frequency side of the signal so as to mask all combination tones. If important increases in frequency discrimination are found these will have to be attributed to the elimination of combination tones, thereby establishing their importance for frequency discrimination of bandfiltered periodic pulse trains.
White noise was fed into a low-pass filter with a cut-off frequency of 1600 Hz. The noise level was such that it would just

mask a pure tone situated in the passband of the noise filter and with a level 17 dB below the level of the central component of the complex tone 200 Hz/2000 Hz (repetition frequency/ filter frequency); it was increased by 3 dB with each halving of the repetition frequency relative to the central component. This noise level was a compromise between a maximal masking effect on the combination tones and a minimal interference with the physical frequency spectrum of the complex tone. The noise level was sufficient to mask a harmonic of the bandfiltered periodic pulse train at 1600 Hz completely. The periodic pulse train was filtered through the same filter as was used in most of the foregoing experiments (B & K 1615; S = 100 dB/oct). The measuring method used was the PEST described in chapter 2 with the roving reference signal described in section 3.5. The stimuli were presented at 40 dB SL and two subjects participated in this experiment. The noise was presented synchronously with the complex tones. Presenting the signals against a continuous noise background did not alter the results.
Fig. 4.1 shows the relative jnd_g's of one observer together with the relative jnd_g's of the same subject obtained with the same measuring method but without the addition of noise (dashed line, closed symbols). The data of the other observer were quite similar. As can be seen in fig. 4.1 the shape of the curve is not affected by adding the noise. For all repetition frequencies the discrimination results are slightly worse in the noise condition.

For the same observer the measurements were repeated with the cut-off frequency set to 1700 Hz, keeping the noise level unaltered. Exactly the same discrimination thresholds were obtained as in the previous condition, with one exception. At g = 140 Hz the sense of the pitch was so ambiguous that with the criterion high-low a much larger jnd_g *was obtained. Using the criterion equal-unequal the discrimination score rose and fell in line with the* jnd_g*'s at other repetition frequencies. Both discrimination criteria could be interchanged for the other repetition frequencies investigated.*

Next it was investigated how frequency discrimination changes with noise level. In this experiment a 1/3-octave broad noise band with centre frequency of 1.6 kHz was added to the complex signal 200 Hz/2000 Hz, instead of a lowpass filtered noise. S/N-ratios were expressed again in dB attenuation of

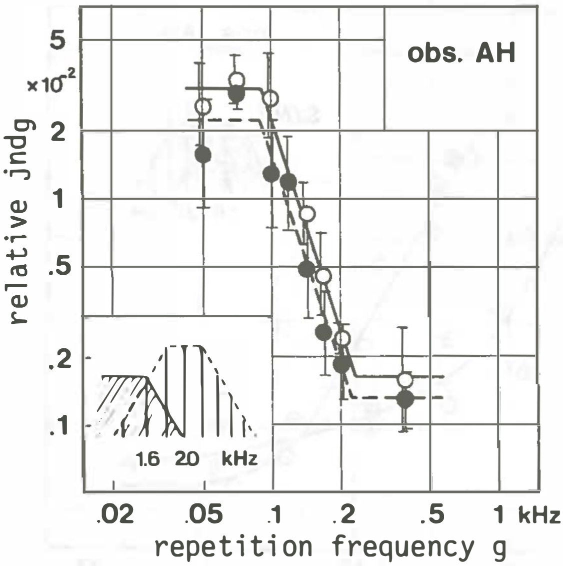


Fig. 4.1 The jnd_g*'s of bandfiltered periodic pulse trains with and without added low-pass noise. The inset shows schematically the relation between signal and noise.*

the noise relative to the noise-level which was required to mask the pulse train when the noise was presented in the 1/3-octave band around 2 kHz. One observer performed this experiment. The results are given in fig. 4.2. The data of the same observer from fig. 3.7a are included. Comparing both, it can be seen that about 10 dB more noise can be added on the low frequency side of the signal filter before the same deterioration in frequency discrimination occurs as with noise and signal in the same frequency band. Addition of noise on the high frequency side of the signal filter has hardly any influence upon the frequency discrimination. Only high noise levels, masking the signal spectrum almost completely, affect frequency discrimination. A few samples at the other repetition frequencies confirmed these observations, viz. that much more noise can be tolerated if added on the low or on the high frequency side.

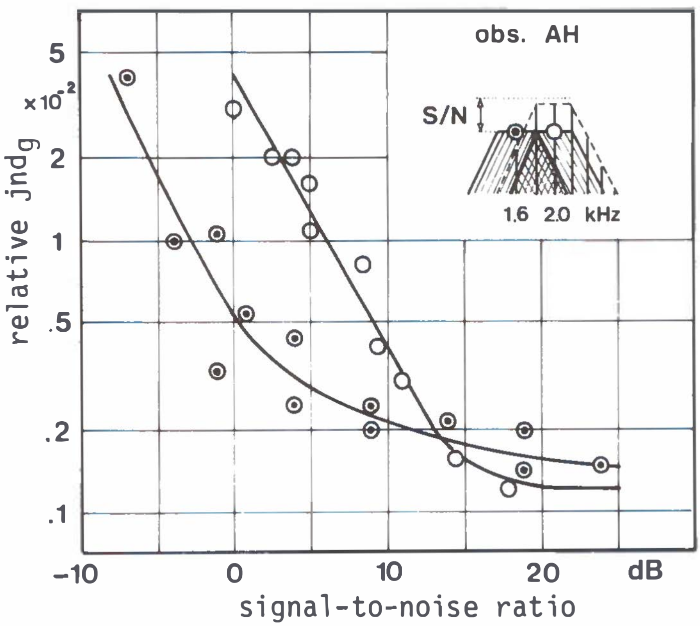


Fig. 4.2 The jnd_g as a function of the signal-to-noise ratio for a repetition frequency of 200 Hz. The 1/3-octave bandfilter of the signal is centred at 2 kHz. The noise is also filtered through a 1/3-octave bandfilter. Two conditions are shown: ○ = noise bandfilter centred at 2 kHz; ⊙ = noise bandfilter centred at 1.6 kHz. For both conditions the noise level is the equal at the same S/N. For S/N = 0 the noise centred at 2 kHz just masks the pulse train.

Discussion

From figures 4.1 and 4.2 it may be clear that the frequency discrimination threshold obtained is not principally governed by the presence of combination tones. Masking all possible combination tones leaves the shape of the characteristic frequency discrimination curve unchanged (fig. 4.1). Still all discrimination results are slightly worse in the noise condition.

A horizontal shift of the sloping part of the curve towards higher repetition frequencies, i.e. towards lower n, is to be expected on the basis of the masking of combination tones. The extent of such a shift can be calculated on the assumption that one of the lower combination tones is determining for the fre-

quency discrimination score. A horizontal shift would be expected analogously from the partly masking of the physical spectrum. The calculated shifts differ too little in both cases with regard to the measuring error, to allow a choice between the two. Both plateaus of the curve are also slightly shifted vertically. Taking this into account, the unavoidable partly masking of the physical spectrum is a sufficient cause to explain the observed effect.
The conclusion could be either of the two following: the combination tones have no significance for frequency discrimination, which would be surprising regarding their importance for pitch perception, or the levels of the combination tones are lower or at best comparable to the levels of the harmonics physically present in the stimulus so that the spectrum is not extended downwards for our particular stimuli. Goldstein (1967) and Smoorenburg (1972a) mention a slope of 80 dB/oct for the level dependence of the combination tone $2f_1-f_2$ on the frequency difference between the primaries when these are around 2 kHz. This is fairly close to the 100 dB/oct slope steepness of the bandfilter used. The levels of combination tones in complex tones consisting of a group of narrowly spaced harmonics, will be considered in more detail in the next section.

For the complex 200 Hz/ 2000 Hz a comparison is made between the frequency discrimination results as a function of the S/N-ratio when a 1/3-octave bandfiltered noise is added to the signal in either the same frequency band or 1/3-octave below. Fig. 4.2 shows that about 10 dB more masking noise can be tolerated in the latter condition. Reverse results would have been expected if combination tones had dominated the discrimination performance. Masking of the primary tones may also disturb combination tones, however. We know of no literature that treats the levels of combination tones when the primary tones are partially masked. Interference with combination tone generation has been shown in case of a threshold anomaly (Smoorenburg, 1972b; Dallos, 1977; Leshowitz and Lindstrom, 1977).

As the higher harmonics contribute relatively little to the frequency discrimination score, as may be clear from the negligible effect on frequency discrimination through the addition of noise on the high frequency side of the stimulus, it follows that the harmonics in the passband of the filter, and presumably the lower ones, are the main determinants of the frequency discrimination thresholds. The degree of their interaction, the degree to which they are resolved spectrally, the degree of their being masked by noise limits the performance. Harmonics with a lower level on the filter skirts or combination tones modify the results to a minor degree. This statement is corroborated by the results of section 3.4, in that masking of the complex tones by a 1/3-octave- or a 1/1-octave-wide noiseband yields the same relative jnd_g's.

4.2 Pulsation-threshold patterns of complex tones

In the previous section it was concluded that the levels of the combination tones in the complex tones employed in the frequency discrimination experiment, might be lower than or comparable to the levels of the physically present harmonics on the low frequency skirt of the bandfilter. The levels of combination tones may be determined directly by means of the cancellation method when they are separately audible (e.g. Goldstein, 1967). The pulsation-threshold method is also suited for the determination of the levels of combination tones (Smoorenburg, 1972b). The results from both methods concur qualitatively but give different results quantitatively. The levels of the combination tones appear to be lower when measured with the pulsation-threshold method (Smoorenburg, 1972b and 1974). When combination tones are not audible separately, as is the case when the frequencies of the primaries are less than 10 per cent apart, the pulsation-threshold method could still be used to determine the levels of the unresolved combination tones. The low frequency slope of pulsation-threshold pattern[1] will be representative for the

[1]*The pulsation-threshold patterns that can be obtained with the pulsation-threshold method are considered to reflect the internal excitation pattern generated by a sound. We understand by an excitation pattern a spatial distribution of neural activity along a scale on to which frequency is projected, scanned with the aid of a probe tone (Plomp, 1976).*
Masking patterns and pulsation-threshold patterns fall within this definition. Physiological parameters characterising this activity pattern need not be known if we use the level and frequency of a probe tone scanning the excitation pattern as a measure of it. Even then a reliable picture of the excitation pattern of a stimulus may be prevented by the phenomenon of off-frequency detection (Houtgast, 1974; Verschuure, 1976).

levels of the combination tone aggregate (Greenwood, 1971).To this end pulsation-threshold patterns have been determined for a number of relevant complex tones. Besides, we were curious to know whether any relationship could be found between the slope steepness of the pulsation-threshold patterns and the frequency discrimination results for filter configurations with very steep slopes (fig. 3.6).

The experimental set-up was described in section 2.3. First of all the pulsation-threshold pattern of a pure tone was determined. For a description of the measuring procedure see chapter 2. In learning to identify the pulsation-threshold the pure tone is the most convenient masker. Besides, the results may serve as a reference. The pulsation-threshold patterns of a pure tone of 2 kHz and 75 dB SPL are given in fig. 4.3 for three observers. They agree with the data from the literature (Houtgast, 1974; Verschuure, 1976).

The determination of a pulsation-threshold pattern of a complex tone is somewhat more difficult. The transition region from clear pulsation to pure continuity of the test tone is often broad and misty. Not all complex tones used in the fre-

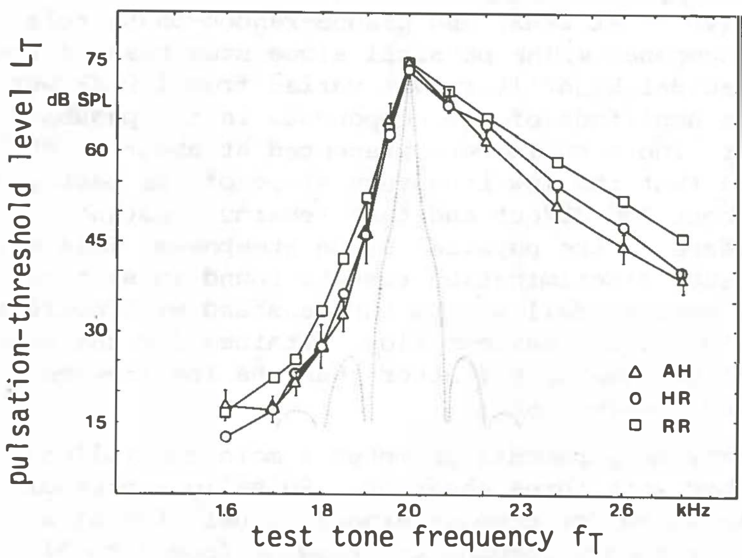


Fig. 4.3 Pulsation-threshold patterns of a pure tone (f_M = 2 kHz; L_M = 75 dB SPL) for three observers. Vertical bars indicate the measuring error. For sake of clarity these are given for one observer only. Dotted line represents the physical spectrum of the gated pure tone.

quency discrimination experiments are suited for the determination of a pulsation-threshold pattern. From preliminary experiments it appears that when the silent intervals between the successive pulses of the bandfiltered periodic pulse train become too long (> 10 msec), as occurs at low repetition frequencies, it becomes extremely difficult to hear the interrupted test tone as a continuous tone. This finds expression in the crumpling up of the pulsation-threshold pattern. Through randomisation of the phase relation between the harmonics of the complex tone, thereby smoothing the waveform envelope, the pattern can usually be regained. From this pilot study we found that from 50 to 70 dB SL the high frequency slope of the pulsation-threshold patterns amounts to about 60 dB/oct, irrespective of the number of harmonics used. The low frequency slope of the pattern appears to be partly dependent on the physical filter slope steepness, but not always in a linear relationship. This was found for bandfiltered pulse trains as well as for bandfiltered noise.
As an example from this pilot study pulsation-threshold patterns are given in fig. 4.4 of synthesized bandfiltered periodic pulse trains with very low repetition frequency (20 Hz), small filterbandwidth (140 Hz at 2kHz) and pseudo-random phase relation between the components. The physical slope steepness of the synthesized trapezoidal bandfilters was varied from 100 dB/oct to 400 dB/oct. The amplitude of the components in the passband were kept constant. The signals were presented at about 55 dB SL. Fig. 4.4 shows that the low frequency slope of the patterns increases up to about 200 dB/oct and then remains constant with further increase of the physical slope steepness. This may bear on the frequency discrimination results found in section 3.3. The patterns seem to fall within the passband with decreasing filter selectivity. The maximum slope attained for the complex tone is still considerably flatter than the low frequency slope of a comparable pure tone.

These preliminary measurements prompted a more controlled experiment performed with three observers. Pulsation-threshold patterns were determined for complex signals consisting of a various number of frequency components (ranging from 2 to 5) within the same frequency band (2000 to 2400 Hz). All frequency components were of equal amplitude and added in cosine phase. The overall level was about 65 dB SL. Distortion products were more than 45 dB down (the limit of our measuring apparatus;

theoretically they were 60 dB down). The complex signals were presented diotically through headphones to the observer. The

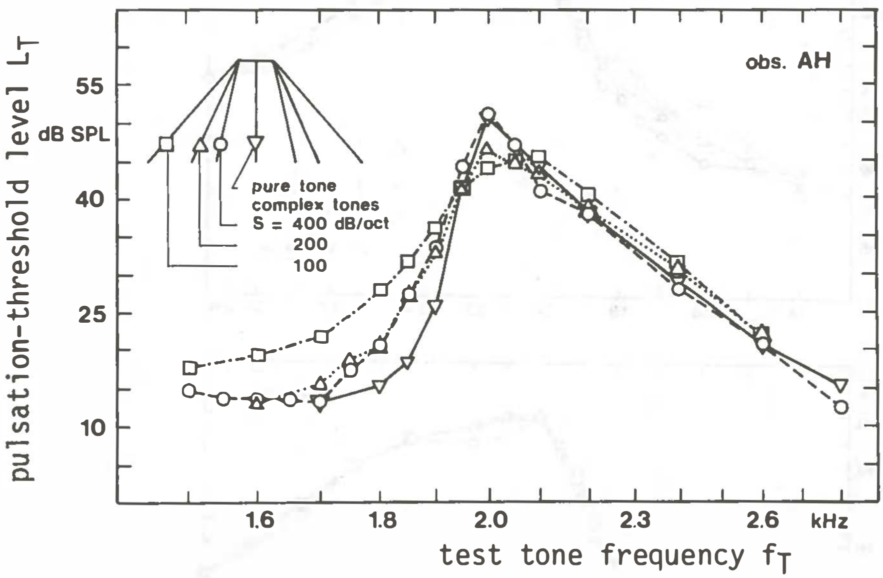
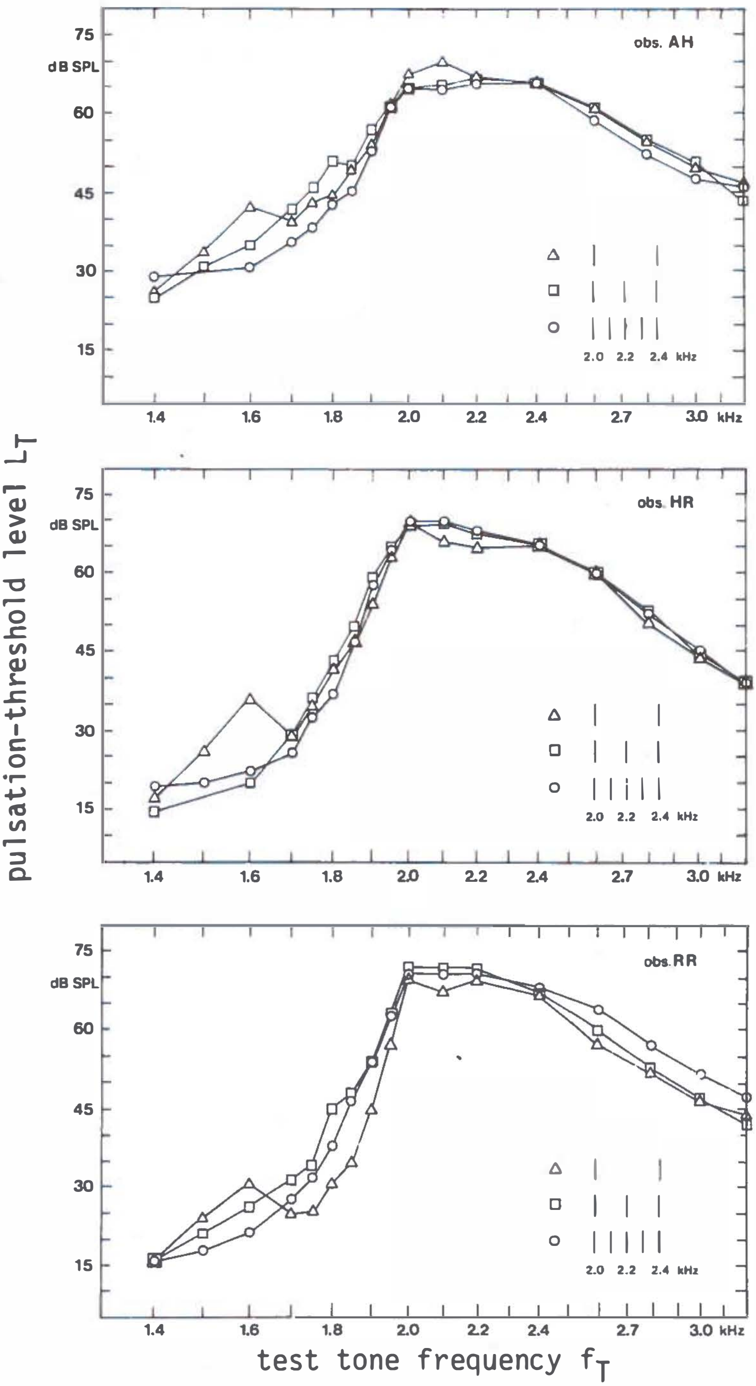


Fig. 4.4 Pulsation-threshold patterns of complex tones consisting of a group of higher harmonics with frequency separation of 20 Hz and pseudo-random phase relation. The spectral envelope was trapezoidal: f_c = 2 kHz, B = 140 Hz. The slope steepness was the parameter: □ = 100 dB/oct; △ = 200 dB/oct; ○ = 400 dB/oct. The sensation level of the masker tones was about 55 dB·SL. For comparison the pattern of a pure tone of equal level as the individual harmonics in the complex tone, is included (▽).

results are given in fig. 4.5. For the two-tone complex (the 5^{th} and 6^{th} harmonic of 400 Hz) a clear bump is visible in the pattern at 1600 Hz corresponding to the combination tone $2f_2-f_1$ (f_1= 2 kHz and f_2= 2.4 kHz). The level of this combination tone relative to the level of the primaries is strongly subject dependent. No valley between the two primaries was found in the pattern. The high frequency slope amounts roughly to 55 dB/oct and is only slightly subject dependent. Also the number of frequency components constituting the complex does not matter, regarding the high frequency slope. On the contrary, the low frequency slope changes with increasing number


obs. AH
obs. HR
obs. RR
75
dB SPL
60
45
30
15
2.0 2.2 2.4 kHz
1.4
1.6
1.8
2.0
2.2
2.4
2.7
3.0 kHz
pulsation-threshold level L_T
test tone frequency f_T

of components, the disappearance of the combination tone at 1600 Hz being the most striking feature. For the observers AH and RR there is an indication of the presence of the third-order combination tone at 1800 Hz for the three-tone complex. The pattern of the other observer slopes smoothly.

The disappearance of the combination tone at 1600 Hz resulting from the insertion of harmonics between the two outermost primaries at 2 kHz and 2.4 kHz was subjected to a closer investigation. The variation in the low frequency slope of the pulsation-threshold pattern of a three-tone complex (primaries at 2.0, 2.2 and 2.4 kHz) was measured for different attenuations of the level of the central component relative to that of the other primaries. The variation in pulsation-threshold level (ΔL_T) at 1600 Hz as a function of the attenuation of the central component is given in fig. 4.6 for two observers. Only 5 to 10 dB attenuation of the central component is sufficient for the complete recovery of the combination tone.

Another possibility to influence the prominence of the combination tone at 1600 Hz appears to be a phase-rotation of one of the components relative to the other primaries. Rotating the phase of the central component over 180^0 gives all possible phase permutations for a three-tone complex (see Buunen, 1975). The effect of this phase rotation upon the pulsation-threshold level at 1600 Hz was measured for the condition that the primaries were of equal amplitude. Two observers participated in this experiment. The results are given in fig. 4.7. The level changes are of the same order as in the case of attenuating the central component. Similar results were found when the phase of the highest primary was rotated over 360^0.

Fig. 4.5 Pulsation-threshold patterns of two-, three- and five-tone complexes in the same frequency band (2.0 kHz to 2.4 kHz). The harmonics were in cosine phase. Presentation level 65 dB SL; 3 observers.

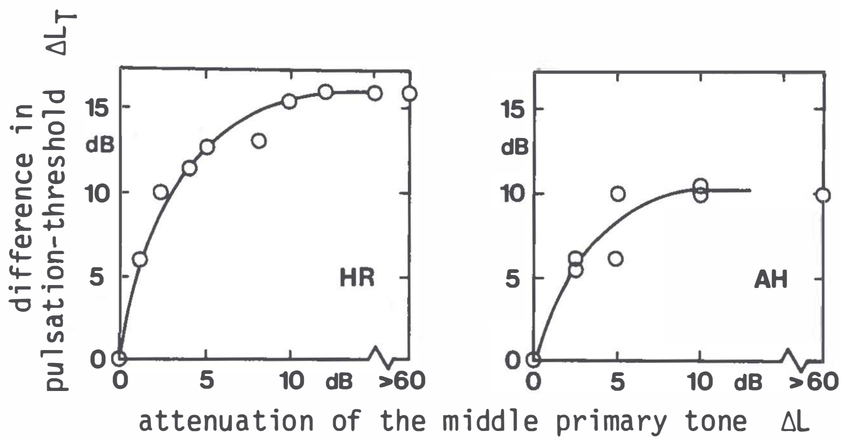


Fig. 4.6 Level changes ΔL_T of the combination tone at f_T = 1600 Hz in a three-tone complex (2000 - 2200 - 2400 Hz) due to the attenuation ΔL of the middle primary tone. L_T has been plotted relative to the level L_T of the combination tone in the three-tone complex with equal level of the primaries ($\Delta L = 0$).

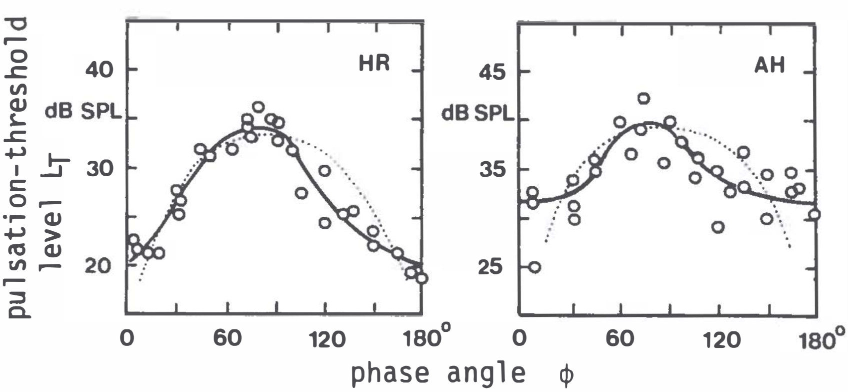


Fig. 4.7 The level of the combination tone at f_T = 1600 Hz as a function of the phase φ of the middle primary tone in a three-tone complex (2000 - 2200 - 2400 Hz). The primary tones are in cosine phase for $\varphi = 0$. The solid curve is drawn by eye through the datapoints, the dotted line is calculated on the basis of vector addition of two combination tones of equal level and a phase difference of 90°.

Discussion

Third-order combination tones show up as clear bumps in the pulsation-threshold patterns of widely spaced two-tone complexes (fig. 4.5). This is in accordance with the literature (Smoorenburg, 1972b). Introducing an intermediate tone, so that the primary tones are closer together makes these bumps vanish and a smooth slope on the low frequency side of the pattern results. The appearance of separate peaks in the pulsation-threshold pattern may be related to the separate audibility of a particular frequency component. It is then somewhat surprising that no valley is found between the components of the two-tone complex. In a ten-tone complex the corresponding harmonics are clearly separated by a valley (Houtgast, 1974); Smoorenburg (1972b) finds a very similar pattern as ours for exactly the same stimulus configuration with a gap-masking procedure. While the high-frequency slope of the pattern is not influenced by the number of components the low-frequency slope changes clearly with the spacing of the primaries (fig. 4.5). For the five-tone complex a series of combination tones would be expected to be present on the low-frequency side, giving the pulsation-threshold pattern a slope in accordance with the dependence of the levels of combination tones on primary spacing (Goldstein, 1967; Smoorenburg, 1972a). The measured slope is, however, considerably steeper. Are combination tones below a group of narrowly spaced harmonics weaker than expected? Is their generation interfered with? The disappearance upon phase rotation over 90^0 of this added primary tone (fig. 4.7) point to interactions between combination tones of different order. Buunen (1976) has shown that such an interaction exists between a combination tone and a harmonic physically present in the stimulus. The observed phase effect could be explained on the basis of vector addition. In our case vector addition of two combination tones of different order and of comparable strength might describe the observed phase effect fairly well (dotted line in fig. 4.7). It is difficult to stick to this explanation, however, because the strength of the interacting combination tones, measured separately in the pulsation-threshold patterns of the appropriate two-tone complexes, viz. f_1= 2000 Hz; f_2= 2400 Hz and f_1= 2000 Hz; f_2= 2200 Hz, differ too much. Level differences of about 10 dB were found. This is also in accordance with the literature (Goldstein, 1967).
Another point is the increase of the combination tone level at

1600 Hz caused by the attenuation of the middle primary tone relative to the other two primary tones (fig. 4.6). Attenuating the level of the middle primary tone by 5 to 10 dB causes an increase in the level of the combination tone to its level in the two-tone complex. From the literature (Helle, 1969/1970; Smoorenburg, 1972b) it is known that the level of the combination tone $2f_1-f_2$ does hardly change with this level difference between the primary tones. A similar behaviour would be expected for the combination tone $3f_1-2f_2$. This is inconsistent with the level effect. At present we have no alternative explanation of the observed effects. A fuller exploration was beyond the scope of the study.
Whatever the explanation of the changing level of the combination tone may be, the maximum attainable level is the best indicator of its real strength and this seems to be in accordance with the expected level dependence on primary spacing. Yet, the phase conditions of the primary tones yielding the steeper slopes in the pulsation-threshold patterns are more in line with the phase relations between the harmonics of the complex tones used in the frequency discrimination experiments than the phase conditions giving the highest combination tone levels. The slope steepness does not reach the value found in the pure tone pattern (fig. 4.3, 4.4 and 4.5). It seems as if a combination tone aggregate exists (Greenwood, 1971), which gives the excitation pattern a maximal steepness of about 200 dB/oct. Not too much weight should be attached to this nominal value, because of the non-linear level dependence of the slope of a pulsation-threshold pattern (Verschuure, 1977). Still the relative relationships remain important, which point to a gradual steepening of the low-frequency side of the pulsation-threshold pattern with increasing physical filter-slope steepness till a certain maximal value. This effect could bear a relationship with the frequency discrimination results of section 3.3. Frequency discrimination may be proportional to the steepness of the excitation pattern on the low-frequency side in the rattle region (see fig. 3.6). This would be in agreement with the model for frequency discrimination put forward by Maiwald (1967) and Zwicker (1970). Coninx (1977) has recently raised objections against the general applicability of such a model to frequency discrimination data, though it might be adequate in this particular case.

In conclusion: The experiments of this section have shown that the strength of not-separately-audible combination tones in narrowly spaced complex tones as used in this study, is lower than would have been expected on the basis of an extrapolation of the levels of separately audible combination tones. This corroborates the finding of the previous section that the rôle of combination tones in frequency discrimination is only a minor one for the complex tones of this study.

CHAPTER 5

FREQUENCY DISCRIMINATION OF HEARING IMPAIRED LISTENERS

5.1 Introduction

Hearing defects are commonly divided in two types, viz. conductive hearing loss and perceptive hearing loss. In case of a pure conductive hearing loss the air conduction threshold of audibility is shifted to higher SPL's while bone conduction thresholds are normal. The threshold elevation is usually different for different frequencies and depends on the nature of the conductive disorder. When the sound level is increased well aboved threshold the perception of sound is more or less comparable to normal sound perception at the same sensation levels. In case of a perceptive hearing loss the sensitivity to air- and boneconducted sounds is diminished to the same extent. Apart from this threshold elevation these hearing impaired listeners suffer very often from a loss in discrimination ability for supra-threshold sounds. This ability to discriminate between different sounds is in clinical practice particularly investigated through speech discrimination tests. Also tests based on discrimination of loudness differences are in common practice. Frequency discrimination tests never obtained a firm footing.

Frequency discrimination of hearing impaired listeners has been investigated mainly for pure tones (see section 1.3). Nearly always an increase of the jnd_f is reported in case of perceptive hearing loss compared to normal hearing listeners. Listeners with a conductive hearing loss obtain the same scores as normal hearing listeners at comparable sensation levels. It is not possible to draw a strict dividing line between the frequency discrimination scores of normal hearing listeners and those of listeners with a perceptive hearing loss. Correlations between pure tone frequency discrimination and speech intelligibility are poor (see section 1.3). It is questionable whether pure tones are suited as a means to investigate a relationship between speech intelligibility and frequency discrimination. About the relation between frequency discrimination and frequency resolution similar statements can be made.

Our investigations concern the frequency discrimination of the repetition frequency of bandfiltered periodic pulse trains. From the foregoing chapters it is inferred that for normal hearing listeners the results depend predominantly on the frequency analyzing capacity of the ear. According to Evans and Wilson (1973) physiologically, the frequency selectivity of the auditory system is already established at the cochlear level. It has been suggested (Evans, 1974; 1975) that a perceptive hearing loss of cochlear origin involves a loss of frequency analyzing capacity. A deterioration of the frequency analyzing capacity of an individual hearing impaired listener should show itself in the results of the frequency discrimination experiment with bandfiltered periodic pulse trains. Also correlation of the frequency discrimination data of complex tones with speech discrimination scores seems more obvious than between the latter and frequency discrimination of pure tones.

5.2 Subjects

For the present aim it would be desirable to have hearing impaired subjects with an exclusively cochlear hearing loss. It is audiologically not easy to label a perceptive hearing loss as purely cochlear. Lesions resulting from a noise trauma are assumed to be exclusively cochlear, though also affection of higher nuclei has been reported (Johnson and Hawkins, 1976). Also abruptly starting high frequency losses, often symmetrical in both ears, are presumably cochlear. Congenital hearing losses, however, may involve both cochlear factors and central lesions. In presbyacusis lesions are diffuse and scattered over the whole auditory pathway. A number of clinical test results may help to augment the probability that the hearing loss is of cochlear origin or has cochlear involvement (Katz, 1972). The presence of loudness recruitment is considered to be an indication of a cochlear lesion. The same applies for Békèsy audiograms type II and speech audiograms that decline for higher SPL's. In the choice of our subjects we have tried, within practical limits, to ascertain the cochlear origin of the hearing loss with these limited means available.

About 60 hearing impaired listeners participated in these experiments, though not all to the same extent. Their age varied between 12 and 77 years. The hearing losses in the frequency

regions that were examined, varied between 40 and 85 dB HL. The tone audiograms were fairly flat (slope $<$ 10 dB/oct) around the frequency region concerned. Relevant audiological details about individual subjects will be given in the following when necessary. All listeners were patients of the Institute of Audiology of the University Hospital at Groningen. They visited the Institute for audiological diagnosis and/or revalidation of their hearing by means of a hearing aid. After that, they participated in our experiments voluntarily. Often they came for a second time. A small group revisited us several times. Nobody had any experience whatsoever with psychoacoustic experiments and all hearing impaired subjects must therefore be regarded as untrained. The subjects got a short instruction about the procedure of the experiment and next it was checked in a few short runs whether they had understood the instruction properly. Strong learning effects were sometimes observed in the beginning of the measurements. Usually, a constant discrimination level was attained rather quickly during the session, presumably due to the measuring method used, to which the visual feedback assisted considerably.
As the subjects suffer from a sensorineural hearing loss it cannot be taken for granted that an individual hearing impaired subject will experience the same subjective sensations as a normal hearing subject when listening to the complex signals used. Labels that are attached introspectively to sounds by normal hearing subjects such as high-low, soft-loud, bright-dark, etc., may be completely wrong to fit the sensations of a hearing impaired listener. To avoid all possible confusion in this matter the hearing impaired subject had only to decide whether two successive signals were equal or not in his opinion. Varying the difference in repetition frequency of the bandfiltered periodic pulse trains a jnd_g was obtained within about ten minutes.
The frequency discrimination data obtained may not represent the best results an individual subject can achieve, due to his lack of training (Gengel, 1969), but in many cases not much improvement can be expected by a longer training period (Butler and Albrite, 1956). Of decisive importance, however, are the discrimination results - for different stimulus configurations - relative to each other. It was verified in a number of cases that the relative relationships remain intact over different experimental sessions, though the absolute values may improve.

Apart from this basic frequency discrimination experiment a part of the hearing impaired listeners participated additionally in related experiments. The results will be presented separately in chapter 6. Especially, ten pupils of a school for hard of hearing at Groningen were examined extensively in seven experimental sessions altogether. Most of their data will be presented individually.

5.3 Experiments

The apparatus used in the basic frequency discrimination experiment with the hearing impaired listeners was the same as for the normal hearing listeners and has already been described in chapter 2 (figs.2.2 and 2.3b). The periodic pulse train was filtered through a 1/3-octave bandfilter (B & K 1615) with slope steepness of about 100 dB/oct. Occasionally a 1/3-octave bandfilter with slopes of 50 dB/oct has been used. The stimuli were presented in 600 msec long intervals separated by a silent interval of 600 msec. The presentation was monaurally through a headphone (TDH 49) with circumaural cushions (001A). The measuring method used was the AX-method. The discrimination criterion to be used was: equal-unequal. The sensation level at which the stimuli were presented was in most cases roughly 25 dB. Higher or lower sensation levels were used occasionally, depending on the magnitude of the hearing loss at the filter frequency under examination. Accordingly, the stimuli were frequently presented at high SPL's. At high SPL's difference tones may become audible (Plomp, 1965), also for hearing impaired listeners. Hoogland (1963) has shown that hearing impaired listeners may hear difference tones at normal levels, even when the primaries are inaudible themselves.
To prevent discrimination from taking place upon changes in frequency of the difference tone, a continuous low-pass noise was also presented to the test ear. The cut-off frequency of this filter was two octaves below the filter frequency of the bandfilter of the pulse train. The slope steepness was 24 dB/oct. The level of the noise was chosen in relation to the signal level so that the difference tone would be sufficiently masked. It is assumed that the noise does not affect the perception of the signal itself. In case of a very asymmetrical hearing loss in both ears the non-test ear was masked with bandpass noise in the same frequency region as the bandfiltered pulse train. Any cross-over will therefore

be eliminated.

A sample of the results is shown in fig. 5.1. Five curves are shown, obtained at different centre frequencies of the band-filter and at different hearing losses (indicated by arrows in the inset). The inset shows the audiograms of the five subjects, all pupils of the school for hard of hearing. An inspection of this figure gives an idea of the many curves deviating from the normal characteristic frequency discrimination curve, that can be obtained. The deviations range from a shift of the lower bend in the curve to lower n-value into a complete disappearance of the bending in the curve. In the latter case a pure tone is as poorly discriminated as a rattle-like sound.

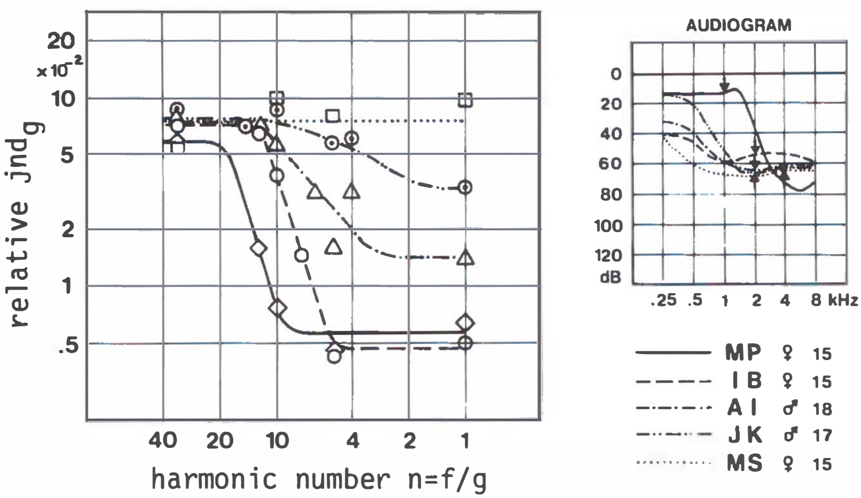


Fig. 5.1 A sample of the various deviating frequency discrimination curves for five hearing impaired subjects. Audiograms are given at the upper right. Arrows indicate the corresponding filter frequencies. The numbers tc the lower right indicate the age of the listeners. Note that in this figure the n-axis is in the opposite direction as in figs. 3.4 and 3.9 to make a better comparison with the data of figs. 5.5 to 5.11 possible.

Sometimes the rattle is subjectively found to be discriminated even easier. Nevertheless, also by these listeners the pure tone and the rattle are perceived quite differently. Similarly, curves deviating from the normal were found for many other hearing impaired listeners that participated in the experiments.

A particular shape of the frequency discrimination curve is not directly related to the amount of hearing loss in the frequency region of interest. For hearing losses above 65 dB HL no normal frequency discrimination curves have been found, however, so that the probability to find a normal frequency discrimination curve diminishes with increasing hearing loss. It was observed that strongly deviating curves are more likely to be found in high-frequency regions than in low.

When all data are pooled it is notable that on the average the measured values for the relative jnd_g for the hearing impaired listeners are higher than for untrained normal hearing listeners. This refers more to pure tone frequency dis-

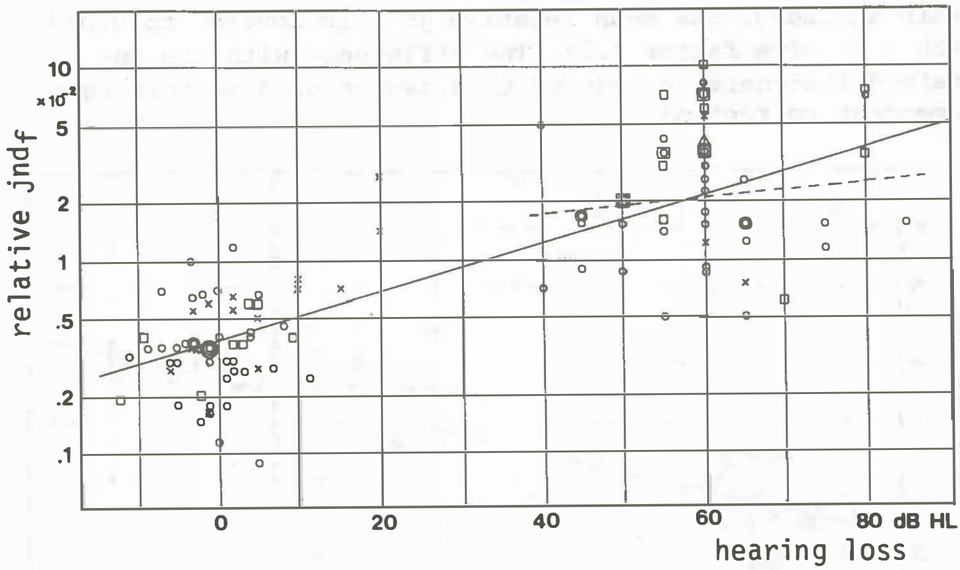


Fig. 5.2 The relative jnd_f of a pure tone as a function of hearing loss. The data of untrained normal hearing listeners and of hearing impaired listeners are shown for three frequencies: × f = 1 kHz; ○ f = 2 kHz; □ f = 4 kHz.
The solid line is the least squares fit to all datapoints.
The dashed line is the least squares fit to the datapoints for hearing losses greater than 35 dB.

crimination than to rattle rate discrimination. The mean relative jnd_f for a pure tone (f = 1, 2 or 4 kHz) obtained for 44 hearing impaired listeners regardless of hearing loss equals 0.02 (standard deviation of a factor 2). For the untrained normal hearing listeners of section 3.7 the mean relative jnd_g score at $n = 5$, which is the same as the relative jnd_f of a pure tone, was found to be 0.0032 (σ a factor 1.7); a difference of about a factor of 6. In fig. 5.2 the relative jnd_f for pure tones has been plotted as a function of the hearing loss at the pure tone frequency. A least squares fit to a straight line is shown for all data as well as for the data for hearing losses over 35 dB.
The influence of age on the frequency discrimination of pure tones as reported by König (1957b), was considered too. Replotting the results of fig. 5.2 with an age dependent correction of the frequency discrimination scores according to König, fig. 5.3 is obtained. Least squares fits to straight lines are again included. The mean relative jnd_f is lowered to 0.013 (with a σ of a factor 2.2). The difference with the untrained listeners is reduced to a factor of 4 by this age dependent correction.

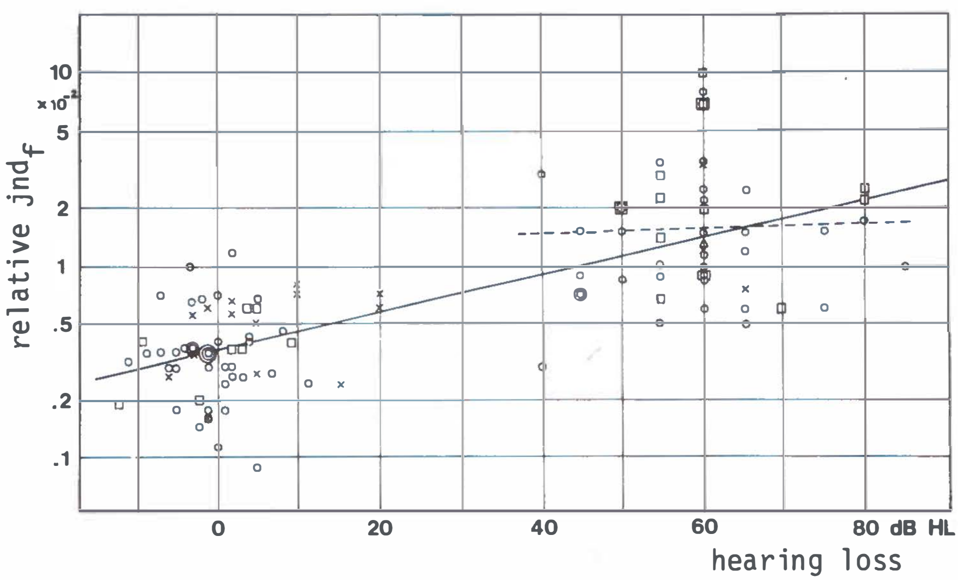


Fig. 5.3 The same as fig. 5.2, except that all data have been corrected for age according to data of König (1957b).

Fig. 5.4 shows the frequency discrimination thresholds in the rattle region (n = f/g = 33.3). There is no change in the jnd_g with increasing hearing loss. The mean relative jnd_g is about 0.10, roughly twice that for untrained normal hearing listeners (20 observers). It is not known whether the same age dependent correlations as for a pure tone apply for the discrimination in the rattle region. Taking into account the data of young hearing impaired listeners only, the mean is lowered to 0.075 and becomes, within measuring error, comparable to normal.

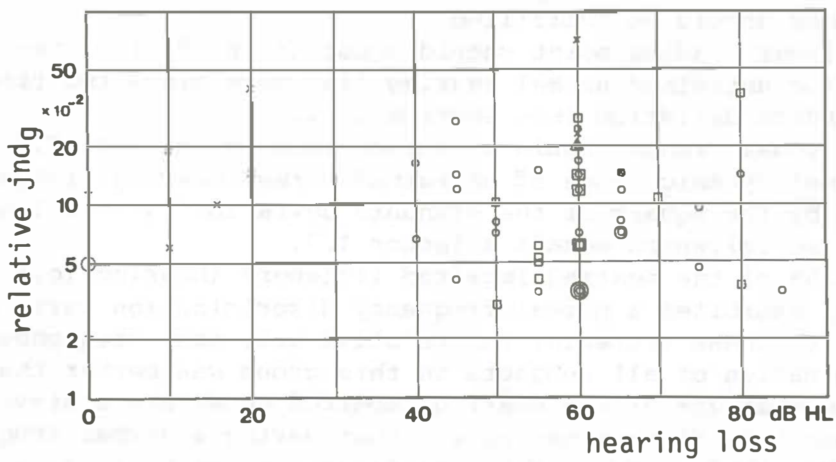


Fig. 5.4 The relative jnd_g in the rattle region (n = f/g = 33.3) as a function of hearing loss for the same hearing impaired listeners as of fig. 5.2 for three filter frequencies: × f = 1 kHz; ○ f = 2 kHz; □ f = 4 kHz. The large symbol on the left is the average jnd_g of untrained normal hearing listeners.

Discussion

From fig. 5.1 it may be clear that the short testprocedure introduced in section 3.7 and meant for the fixation of the characteristic frequency discrimination with respect to the n-axis is unfeasible where perceptive hearing loss in concerned. This became clear rather quickly because a rigid application of the rules of the testprocedure resulted in very high n-values for the lower bending point of the curve. The failure of the short testprocedure is mainly due to the reduction of the difference in discrimination level of the two plateaus. The ratio between the relative jnd_g in the rattle region and the relative jnd_f for a pure tone of the corresponding filter frequency will be called the "dynamic range" of the frequency discrimination curve.

Because there is a gradual transition from the normal frequency discrimination curve to the completely flat curve (see fig. 5.1) we have the problem of defining the criteria by which the frequency discrimination curve may be accepted as normal. The shape of the normal frequency discrimination curve cannot easily be characterised by a single parameter. At least two conditions should be fullfilled.

1. The lower bending point should occur for $n > 7$, i.e. the result for untrained normal hearing listeners minus two times the standard deviation (see section 3.7).
2. The dynamic range should be larger than or equal to 7, i.e. the normal dynamic range of untrained normal hearing listeners divided by the square of the standard deviation(2σ on a logarithmic scale),which equals a factor 1.7.

Nearly 25% of the hearing impaired listeners (hearing loss > 35 dB) exhibited a normal frequency discrimination curve according to these criteria. The relative pure tone frequency discrimination of all subjects in this group was better than 0.02. Another 25% of the hearing impaired observers achieved this pure tone discrimination whithout having a normal frequency discrimination curve. With age dependent corrections this percentage would even be greater (about 35%). All remaining hearing impaired listeners had a relative $jnd_f > 0.02$ as well as an abnormal frequency discrimination curve.

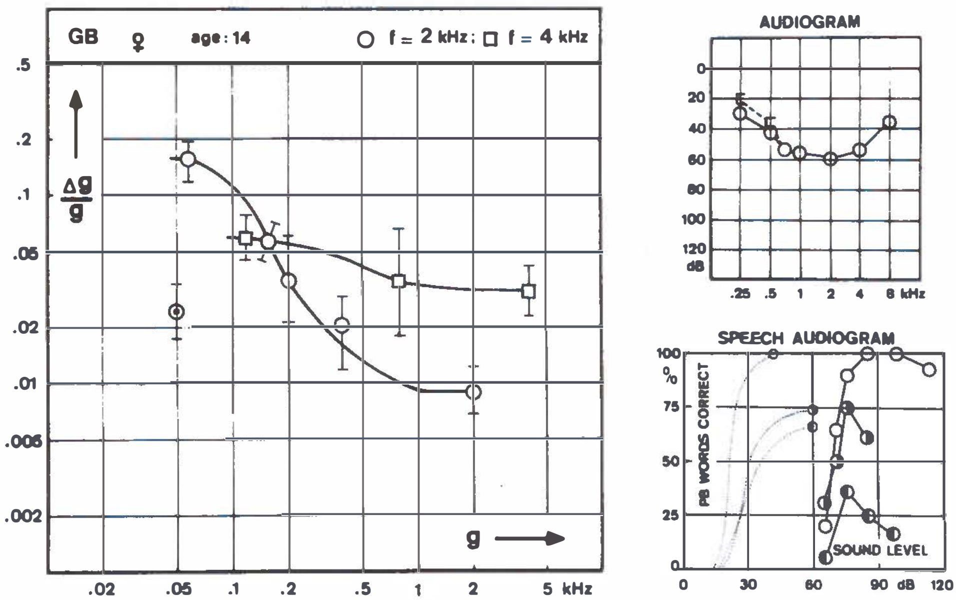
About 70 per cent of all frequency discrimination curves satisfying the second criterion complied also with the first. The position of the lower bend is often difficult to determine. Searching for a single substitute criterion for the normality of the frequency discrimination curve, it was found that for normal frequency discrimination curves the ratio: (relative jnd_g in the rattle region)/(relative jnd_g at $n = 10$) is larger than 3.5, while for practically all other curves this ratio was smaller. Unfortunately the jnd_g at $n = 10$ was determined only for a smaller group of subjects.

With regard to the relation between speech intelligibility and frequency discrimination it appeared that the relative $jnd_f$of a pure tone nor the dynamic range showed a better correlation with the maximum PB-word scores than the Fletcher index. In spite of the general trends in the results there is a considerable spread which makes predictions of individual results from the averaged data precarious. We will now focus to some individual results.

5.4 Individual results

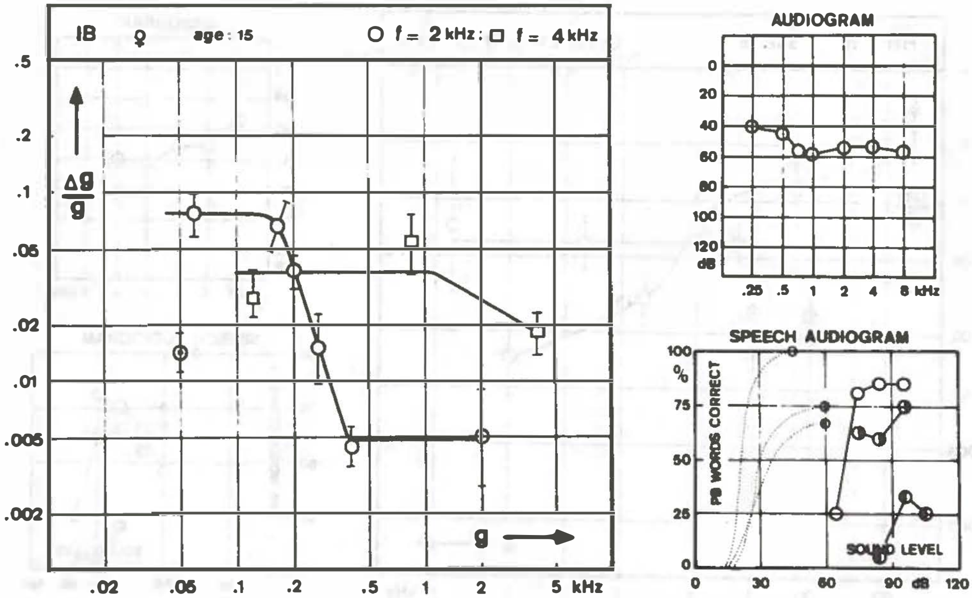
Due to the limited measuring time available, in most of the cases frequency discrimination at only one filter frequency could be explored. When we did have some more time at our disposal a number of other experiments in the same frequency region seemed sometimes of more interest than repeating the frequency discrimination experiments at another filter frequency. Nevertheless, for several hearing impaired listeners frequency discrimination at two filter frequencies was investigated. First we will direct our attention to the results of the pupils of the school for hard of hearing, because they participated in most experiments. The apparatus, the experimental conditions and procedures were the same as already mentioned in the previous section. The next six figures contain the frequency discrimination results of six of them (figs.5.5 to 5.10)for two filter frequencies. On the upper right side of the figures the audiogram of the ear under investigation is given. On the lower right side the speech audiogram for that ear is depicted.
From figures 5.5 to 5.10 it can be seen that, as mentioned before, the worst frequency discrimination curve is most likely to be found for the higher filter frequency. It is also illustrated that even for the same subject completely different curves can be found for different frequencies but with the same hearing loss (figs. 5.6, 5.8 and 5.10). This means that also the pure tone frequency discrimination data may differ widely in different frequency regions for the same subject though the hearing loss is the same.
As to the speech audiograms, they contain apart from the normal intelligibility scores also the intelligibility scores for high-pass (◐,◖) and low-pass filtered (◑,◗) PB-words. The cut-off frequency of both the high-pass and the low-pass filters was 1900 Hz. The filter slope amounted to 96 dB/oct in both cases. For the PB-word lists used (the Leiden PB-word lists), the mean maximum scores and the reception thresholds for the three conditions were measured for 9 untrained, normal hearing listeners to serve as a reference. The reception threshold for

undistorted PB-words was at 22 dB SPL, whereas this point shifted to 30 dB and 35 dB respectively, for the LP- and HP-filtered PB-words. These results have been included in figs. 5.5 to 5.10 as dotted lines. The data points for the high-pass



Figs. 5.5 to 5.10 The relative jnd$_g$ in repetition frequency of bandfiltered periodic pulse trains for two filter frequencies for several hearing impaired listeners. The compound symbols ⊗ , ⊙ and ⊡ show the relative jndf$_c$ in filter frequency. The pure tone audiogram of each subject is shown at the upper right, while the speech audiogram is shown at the lower right. The speech audiogram includes the scores for LP- (◑,◗) and for HP- (◐,◖) filtered PB-words. The scores for normal hearing listeners are given as dotted lines for the same conditions.

and low-pass filtered speech sounds are plotted at the sound level of the corresponding unfiltered speech words. This means that the actual sound level is lower for the filtered condition. This applies especially to the high-pass filtered words. The maximum discrimination score was lowered in both filtered conditions with respect to the normal condition (100%) viz. 75% for the LP-filtered PB-words and 70% for the high-pass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dB
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4
8 kHz
SPEECH AUDIOGRAM
100
%
75
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25
0
PB WORDS CORRECT
SOUND LEVEL
0
30
60
90 dB
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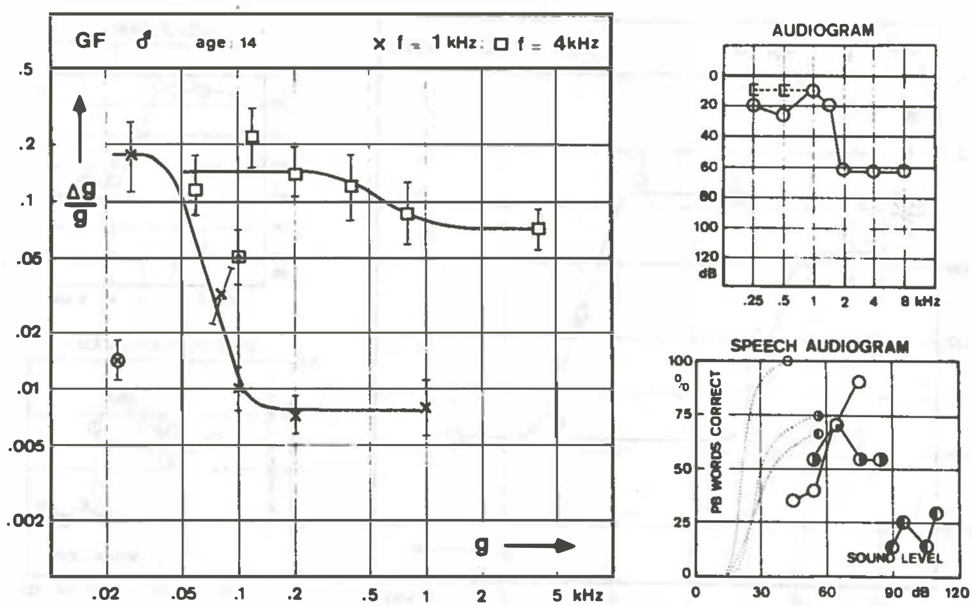
Fig. 5.6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AUDIOGRAM
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8 kHz
SPEECH AUDIOGRAM
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PB WORDS CORRECT
SOUND LEVEL
0
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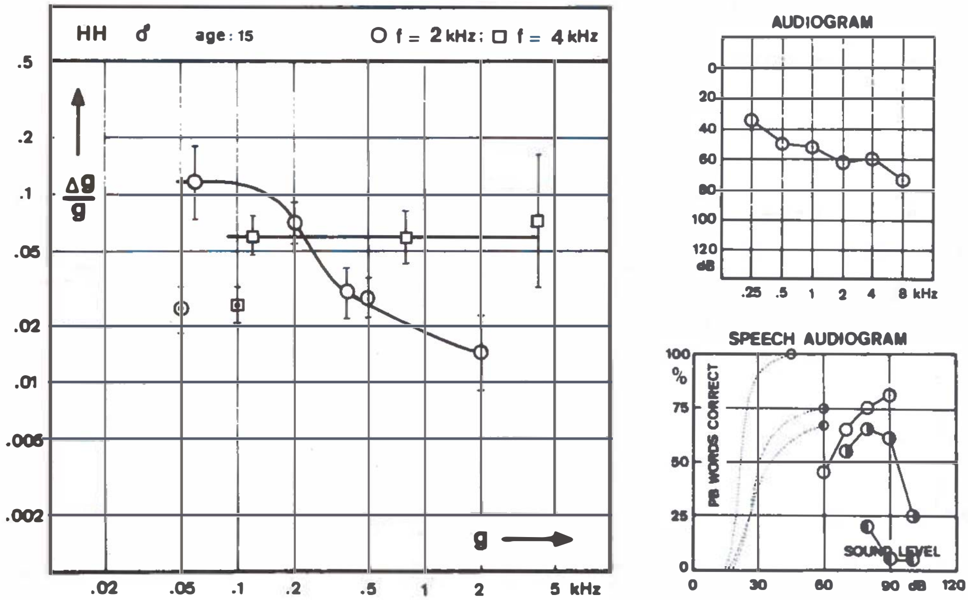
Fig. 5.7


HH ♂ age: 15
○ f = 2 kHz; □ f = 4 kHz
Δg/g
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AUDIOGRAM
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SPEECH AUDIOGRAM
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0
PB WORDS CORRECT
SOUND LEVEL
30
60
90 dB
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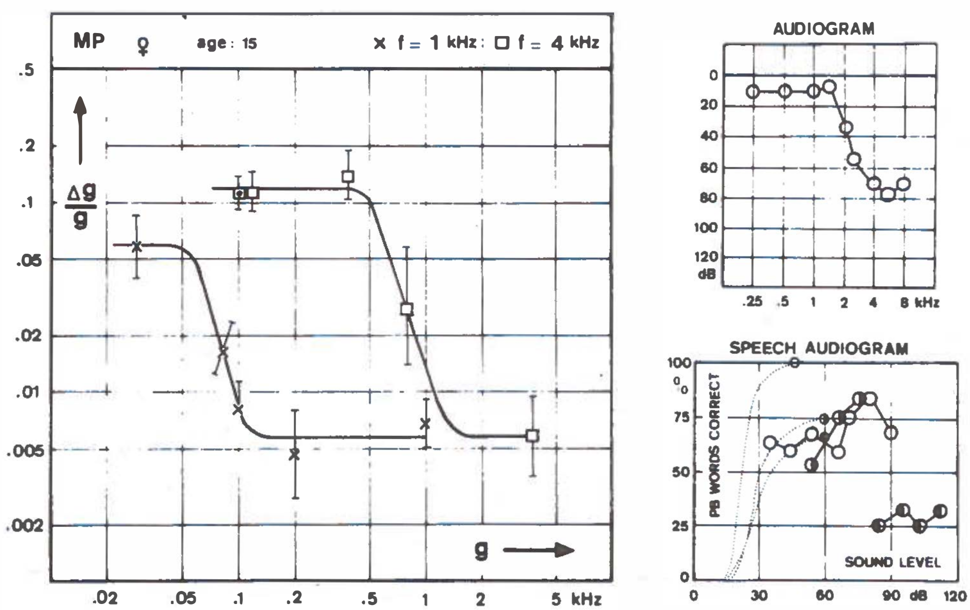
Fig.5.8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× f = 1 kHz; □ f = 4 kHz
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Fig.5.9

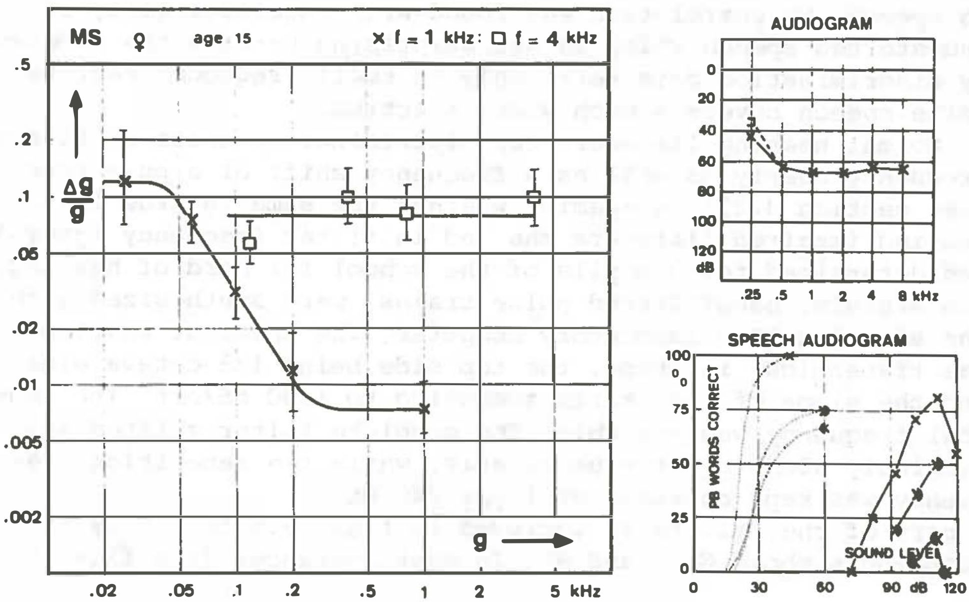


Fig. 5.10

filtered PB-words. This is in agreement with the literature (see Stevens, 1951). From the speech audiograms of figures 5.5 to 5.10 it can be seen that all six pupils reach a fairly high speech discrimination score (>80%) at optimal intensity levels. The intelligibility scores for the low-pass filtered conditions are equal to or somewhat lower than the scores in the all-pass condition. This is comparable to the results of normal hearing listeners. Often no appreciable shift in repetition threshold was found. High-pass filtered PB-words appear to be much less intelligible to the hearing impaired subjects. The maximum score measured was 35%. Sometimes hardly any word is correctly reproduced. In these cases the frequency content of the words lying above 1900 Hz yields by itself no information to make the words intelligible, but in combination with the LP-filtered part of the speech sounds it contributes to the overall intelligibility, so that the maximum discrimination scores of unprocessed speech words exceed those of LP-filtered words. From figures 5.5 to 5.10 it can be seen that for all six hearing impaired listeners a strongly deviating frequency discrimination curve at f = 4 kHz was found. So there is some conformity between frequency discrimination of bandfiltered periodic pulse trains and speech intelligibility of HP-filtered speech. No correlation was found with intelligibility of undistorted speech which is not surprising because the frequency discrimination data refer only to small frequency regions while speech covers a much wider spectrum.

Normal hearing listeners can discriminate a shift in filter frequency nearly as well as a frequency shift of a pure tone (see section 3.3). To examine whether the same is true for hearing impaired listeners the jnd in filter frequency (jnd_{fc}) was determined for 9 pupils of the school for hard of hearing. The signals, bandfiltered pulse trains, were synthesized with the aid of a PDP8 laboratory computer. The spectral envelope was trapezoidal in shape, the top side being 1/3-octave wide and the slope of the skirts amounting to 1000 dB/oct. The central frequency was variable. The complete filter shifted accordingly along the frequency axis, while the repetition frequency was kept constant at ($f_{ref.}$/40)Hz.
A part of the results is included in figs. 5.5 to 5.9 by the compound symbols ⊗, ⊙ and ⊡ . In most instances (see figs. 5.5

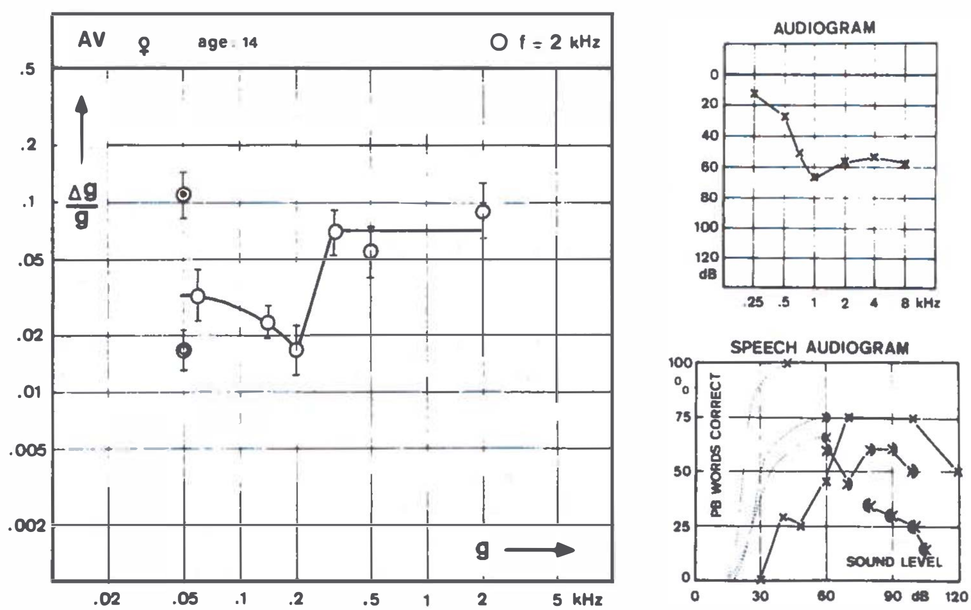


Fig. 5.11 Same as figs. 5.5 to 5.10, but for only one filter frequency. ⊙ *represents the relative* jnd_{f_c} *in filter frequency;* ◉ *represents the relative* jnd_{f_c} *when the repetition frequency is harmonically shifted too.*

to 5.8) the same relationships are found as for normal hearing listeners. In the cases in which the dynamic range of the frequency discrimination curve is very small the relative jnd_{f_c} is smaller than the relative jnd_f (see figs. 5.7 and 5.8: f = 4 kHz). The results of one subject are noteworthy (see fig. 5.11). Here the discrimination results for the rattle is better than that for the pure tone. Discrimination of a shift in filter frequency corresponds in the normal way with the discrimination of the pure tone. When, however, the repetition frequency of the pulse train is varied proportionally to the shift in filter frequency the discrimination score improves and becomes comparable to the frequency discrimination of the rattle.
This case was unique.

5.5 Discussion

Considering the average frequency discrimination threshold for pure tones of hearing impaired listeners, it is clear that it is significantly worse than the average jnd_f of untrained normal hearing listeners. Even when age corrections have been made a difference of a factor 4 remains. Arlinger (1976) has reported a difference of a factor 2.8 for more intensively trained listeners. Maybe these differences are attributable to the loss of viable auditory nerve fibres accompanying a hearing impairment. The interindividual spread in the jnd_f's is very large (see fig. 5.2). This pertains to the data of hearing impaired listeners as well as to those of untrained normal hearing listeners. It is presumably partly due to their lack of training but in particular for hearing impaired listeners also of fundamental origin. This can be derived from data of Butler and Albrite (1956), viz. some of their hearing impaired subjects showed a remarkable improvement in frequency discrimination after prolonged testing, other stuck at a poor discrimination level even after training. It is therefore very difficult if not unfeasible, to draw a strict dividing line between normal and pathological frequency discrimination of pure tones.

It has been suggested that deterioration of frequency discrimination of pure tones is directly related to the amount of hearing loss at the frequency concerned (Meurman, 1954; Ross et al., 1965; Gengel, 1969; Leshowitz, 1977 personal communication). Our results are not unequivocal on this point. Considering all data of the hearing impaired listeners together with the frequency discrimination data of untrained

normal hearing listeners and fitting them by a straight line according to the least-squares method, a line is found with a positive slope of about a factor 17 increase in relative jnd_f per 100 dB hearing loss (fig. 5.2). If the data are corrected for the age dependence of the jnd_f, the slope is nearly halved. This result is significant at the 0.1% level. It must be kept in mind however, that the data are not regularly distributed along the hearing loss axis. There are rather two clusters: one around 0 dB and one around 60 dB hearing loss. Considering only the results of hearing losses exceeding 35 dB the slope of the straight line is largely reduced (less than a factor 3 per 100 dB); moreover, the data points correlate hardly better than a random sample to this line. A discontinuity in the relative jnd_f at about 35 dB hearing loss cannot therefore be excluded. Harrison and Evans (1977) have found that the tuning of cochlear nerve fibres from pathological cochleas is non-linearly related to the degree of threshold elevation. The 10 dB-bandwidth of the physiological tuning curve becomes suddenly very broad at a threshold elevation of about 40 dB. This may correspond to the discontinuity as suggested above.
A further check of the supposed rule, that the jnd_f is proportional to the amount of hearing loss, can be made by comparing individual results at different hearing losses for the same subject. A number of results accords to the rule (see figs. 5.7 and 6.7), whereas others argue against it (see figs. 5.5, 5.6, 5.8, 5.9 and 5.10). Similar results have been reported by Kōnig (1961). It should be realized that the experimental paradigm allows for all possible clues apart from frequency or pitch to be used for the discrimination. Especially in cases of cochlear hearing loss it is obvious that when loudness recruitment is present small loudness differences might provide a discrimination cue. Care was taken, however, that the hearing threshold around the frequency region under investigation, was fairly flat. Discrimination on loudness differences will have been the exception rather than the rule. We believe that in general the data can be interpreted as they stand.
We are inclined to conclude that a simple linear relation between hearing loss and frequency discrimination, though applicable to the pooled results, is not appropriate for the individual case. It would be surprising if the nature and the extent of the lesion, which is only roughly indicated by the amount of threshold elevation, should be irrelevant to discrimination thresholds.

Frequency discrimination in the rattle region is independent of the amount of hearing loss. This holds even for the pooled results. The interindividual spread is comparable to that for pure tone frequency discrimination. The average jnd_g is only slightly worse than the average jnd_g for normal hearing listeners. It may be concluded that for many hearing impaired listeners the discrimination of temporal features such as the waveform envelope repetition rate is fairly normal.

In chapter 3 it was argued that the frequency analyzing capacity of the auditory system shows up in the lower part of the characteristic frequency discrimination curve ($n < 20$). As soon as some frequency analysis of the stimulus becomes possible, the relative jnd_g decreases with regard to the relative jnd_g in the waveform envelope repetition rate. With this interpretation the curves of fig. 5.1 might well be a manifestation of a progressive loss in frequency analyzing capacity. The worst situation is given by the dotted straight line: pure tone and rattle frequency discrimination are equal. Frequency resolution is very bad then, or perhaps completely lost.

However, another explanation of a flat frequency discrimination curve presents itself. It may be recalled that for normal hearing listeners a flat frequency discrimination curve is found for very steeply sloping filters (slope > 200 dB/oct, see section 3.3). It can be imagined that for hearing impaired listeners having a diminished frequency resolving power, this might occur already for smaller slope steepnesses. Therefore the filter with slope steepness of 100 dB/oct, that was used in the experiments, might have been too steep so that a flat frequency discrimination curve results. There are a number of objections against this explanation, although we did not systematically measure the jnd_g in the rattle region as a function of the filterslope for hearing impaired listeners. First of all, it is not the decreasing jnd_g, but the increasing jnd_f, which straightens the frequency discrimination curve. This is illustrated in fig. 5.1 for different subjects, but more convincingly in figs. 5.7, 5.10 and 6.5 for the same subjects. Further, a few measurements were made of the jnd_g for bandfiltered pulse trains when the filterslope was 50 dB/oct, for subjects exhibiting a flat frequency discrimination curve. No differences have been found with the data belonging to the steeper bandfilter (100 dB/oct) (see fig. 6.7). Finally, the relative jnd_{f_c} is smaller than the relative jnd_g ($n = 33.3$) even for completely flat frequency discrimination curves (figs.

5.7 and 5.8).

It was observed that in many cases of otherwise flat frequency discrimination curves the relative jnd_f for the corresponding pure tone was smaller than the relative jnd_g. This poses the question whether the relative jnd_f has to be considered as essentially belonging to the lower plateau of the frequency discrimination curve or not. It is easily imaginable that with a strongly asymmetrical excitation pattern of a pure tone the relative jnd_f could be small, while at the same time complex tones cannot be resolved spectrally, giving larger relative jnd_g's, so that a flat frequency discrimination curve results with the pure tone out of line.

Although no direct measure of the frequency analyzing capacity can be derived from the frequency discrimination data, a rough indication of it can be gathered from the shape of the frequency discrimination curve. With a completely flat curve frequency analysis is deteriorated so much that it is no longer measurable by frequency discrimination. Especially the ratio between the relative jnd_g at $n = 10$ and the relative jnd_g in the rattle region should be considered, because the discrimination accuracy at $n = 5$ could be simply pure tone frequency discrimination for hearing impaired listeners due to the tenuous spectral composition of that complex tone.

The discrimination results of a change in filter frequency were in most cases comparable to normal as regards the relation to pure tone frequency discrimination. A few cases were found in which the jnd_{fc} was smaller than the jnd_f. This may be due to the size of the measuring error, but could also be due to the fact that hearing impaired listeners do find the complex tones more substantial than pure tones. This pertains only to those listeners who exhibit a flat frequency discrimination curve. Perhaps the stimulation of a broader frequency region is benefical.

The findings, that the probability to find a normal frequency discrimination curve decreases with increasing hearing loss, and also with higher filter frequencies might be related. Unfortunately, no hearing impaired listeners with an exclusively low frequency hearing loss were examined. However, at f = 1 kHz and 2 kHz normal frequency discrimination curves have been found for hearing losses up to 65 dB HL, while at f = 4 kHz no such curves were found even at lower hearing losses.
Also within the same hearing impaired listeners at the same hearing loss the results for the higher filter frequency were

always worse. These arguments favour the conclusion that the above mentioned effects are independent.

About the relationship between frequency discrimination and etiology of hearing loss we can hardly do anything else than guess. A certain tone audiogram does not necessarily indicate a lesion in a specific cochlear element (Wersäll, 1973, Suga and Lindsay, 1975). Dallos and co-workers (1975; 1976) have shown that at least some ototoxic agents produce a well defined lesion in the haircells, especially in the outer haircells, which corresponds with a threshold shift in the tone audiograms. Lesions due to noise trauma are less sharp, but frequently corroborate the tone audiogram especially when there is an abrupt high tone loss (Hawkins et al., 1976; Johnson and Hawkins, 1976). Yet, threshold elevations may be found in regions with no or slight haircell losses and vice versa. The relation between tone audiogram and cytocochleogram is not always good. So the presence of a haircell does not necessarily imply its correct physiologically functioning. In case of presbyacusis the degeneration patterns are more diffuse. Especially a decrease in the population of spiral ganglion cells seems to be involved (Suga and Lindsay, 1975). Congenital sensorineural hearing loss is hardly documented, but may involve apart from cochlear lesions also more central lesions.

The precise origin of the hearing loss of too many of our hearing impaired listeners is unknown or uncertain. This makes it difficult to categorize the data. Still, we examined a fair number of listeners with abrupt high frequency hearing loss. In general pure tone discrimination thresholds are raised in the affected frequency region: relative $jnd_f > 0.02$ in 60% of the cases. Moreover, in most cases (90%) an abnormal frequency discrimination curve is found. This may indicate a relation between loss of haircells and a decreased frequency analyzing capacity. The group of patients with noise induced hearing loss show much more variation and fairly good frequency discrimination may be found. According to data of König (1961) an elevated jnd_f should be found in the damaged frequency region in case of acoustic trauma. Perhaps some hearing losses of our subjects were not purely noise induced. Too few subjects with presbyacusis were seen to say anything definite about frequency discrimination for this group. For the much larger group of subjects with congenital hearing defects the variation in the results and presumably also in the origin of their hearing losses is too large to make clear divisions.

A direct relation between a raised jnd_f and the presence of loudness recruitment has been forwarded by Schubert (1951).

Harris (1955) and König (1961) have strongly argued against it. Our data are not pertinent to this issue but seem to concur with the viewpoint of Harris and König.
The not yet fully explored relation between the present frequency discrimination data and the many different, known hearing pathologies makes a direct clinical application in the form of a particular test unfeasible for the time being. But the fact that no prediction of the frequency discrimination data can be made based on clinical audiological data commonly used, makes frequency discrimination with complex tones apt as a tool for a finer diagnosis of a perceptive hearing loss. A good classification has to be awaited.

No clear relation between frequency discrimination and speech intelligibility could be found. This may partly be due to the fact that the frequency discrimination data were only collected in one or two restricted frequency regions, whereas a wider frequency range is involved in speech perception. Moreover, speech intelligibility involves more than just the discrimination of frequencies. Nevertheless a slight indication to a positive correlation between the two was found by comparing the speech intelligibility scores for HP-filtered PB-words and the frequency discrimination data at the corresponding filter frequencies.

5.6 Frequency discrimination and pitch perception; some additional experiments

For normal hearing listeners the frequency discrimination task is subjectively performed by comparing pitch, provided a pitch exists. Parallels between frequency discrimination and pitch perception have already been discussed in chapter 3. For hearing impaired listeners no pitch criterion need have been used for frequency discrimination, as only the equality or not of a stimulus pair had to be decided. What might be expected about the perception of pitch by hearing impaired listeners on the basis of the results of this chapter thusfar and in the light of recent pitch theories? For many of the hearing impaired listeners that participated in the previous experiments we concluded from their frequency discrimination data that their frequency analyzing capacity was very poor and in the next chapter the same will be shown from the psychophysical tuning curves. Peripheral frequency analysis remains an outstanding feature of the process of pitch derivation. Loss of frequency analyzing capacity could then not be without repercussions for pitch perception.

With a few hearing impaired listeners a small experiment was performed in which it was investigated whether they are able to make pitch orderings. To this end pairs of complex tones were used with the same spectral extent but with different pitches (see fig. 5.12). The listeners had to decide in a forced choice procedure which tone of a pair had the highest pitch. In order to verify whether the observers are able to order signals correctly on a high-low scale two pure tone pairs were judged in the same session.

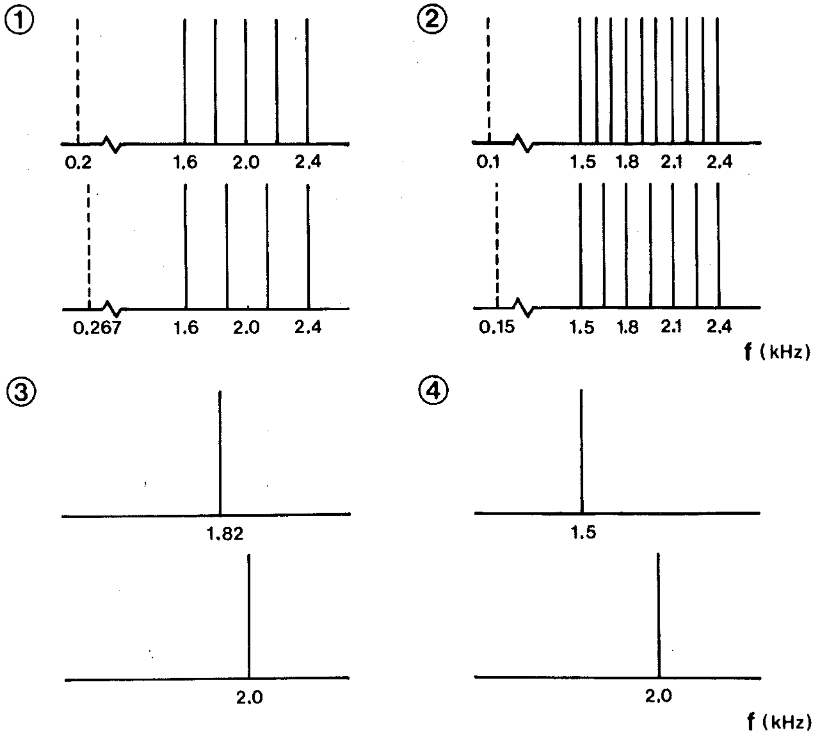


Fig. 5.12 Frequency spectra of the four stimulus pairs in the pitch discrimination experiment.

① *The harmonics 8 to 12 inclu. of g = 200 Hz versus the harmonics 6 to 9 inclu. of g = 266.7 Hz.*

② *The harmonics 15 to 24 inclu. of g = 100 Hz versus the harmonics 10 to 16 inclu. of g = 150 Hz.*

③ *Pure tones with frequency of 1.82 and 2.0 kHz.*

The results are listed in table 5.1 for seven hearing impaired listeners; a "+" signifies that the signals could correctly be ordered with a confidence percentage of 95%, if not an "o" is given; a "-" indicates that the pitch jump was interpreted in the opposite direction. Only the smallest frequency jump of the pure tone pairs presented some difficulties. This is, however, not quite unexpected in view of the former frequency discrimination scores of these hearing impaired listeners. Still the labelling high-low can be done correctly. This is important because nearly all pitch jumps of the complex tones were judged correctly. Spectrally the complex tones to be compared cover the the same frequency region and differ only in the number of harmonics within this region. Without a good frequency analyzing capacity there is no way to tell them apart in the frequency domain. A distinction can be made upon the periodicity of the waveform envelope. Yet, the hearing impaired listeners attach the label high-low correctly. Although we do not know whether the hearing impaired listeners perceived the same pitch that normal hearing listeners perceive, a sense of pitch is apparently conveyed by the periodicity of the waveform envelope.

Table 5.1

obs.	pitch discr.				100%-SAM				quasi-FM			
	1	2	3	4	1	2	3	4	1	2	3	4
HH	+	+	+	+	o	+	+	+	o	o	o	o
JK	+	+	o	+	o	o	+	+	o	o	o	-
PvdS	+	+	o	+	o	+	+	+	o	o	o	o
FH	+	+	+	+	o	+	+	+	o	+	+	+
AV	o	+	o	o	o	o	o	+	o	o	+	+
BY	+	+	o	+	—				—			
KG	+	+	+	+	—				—			

Another possibility could be that the central pitch processor is triggered by the waveform envelope periodicity so that the rank number of the lowest harmonic of the complex tone can be estimated roughly. Nevertheless, pitch theories should be modified to accomodate these findings. Some pilot experiments with complex tones having conflicting pitch information made it clear that pitch perception of hearing impaired listeners is a complicated matter and deserved a more careful exploration than hitherto has been the case (Purvis and Brandt, 1973).

In order to check whether the periodicity of the waveform envelope is indeed so important, a number of the same hearing impaired listeners participated in another small experiment in which the modulation frequency of either 100% sinusoidally amplitude modulated tones or quasi frequency modulated tones had to be discriminated. The power spectra of the 100% SAM- and quasi-FM tones are identical for the same modulation frequencies, but their waveforms are different, because the carrier frequency of the quasi-FM tone is 90^0 out of phase.
In formula:

100% SAM tone : $S(t)=\sin(2\pi ft) + \frac{1}{2}\sin(2\pi(f+g)t) + \frac{1}{2}\sin(2\pi(f+g)t)$.

quasi-FM tone : $S(t)=\cos(2\pi ft) + \frac{1}{2}\sin(2\pi(f+g)t) + \frac{1}{2}\sin(2\pi(f+g)t)$.

Discrimination differences could be expected on the basis of differences in the peakedness of the waveform envelope, which is much greater for the SAM tone than for the quasi-FM tone. The following modulation frequencies had to be discriminated with a carrier frequency f = 2 kHz: 1. 200 and 210 Hz, 2. 200 and 220 Hz, 3. 200 and 240 Hz, 4. 200 and 280 Hz. Normal hearing listeners perform equally well in both conditions; they hear pitch differences. The results for hearing impaired listeners are listed in table 5.1. The notation is as before. For three listeners strong differences were noticed between the discrimination of the modulation frequency of the SAM- and quasi-FM tones. The latter presented insuperable difficulties. This result is compatible with what should be expected on the basis of differences in peakedness of the waveform envelope. Other causes of the observed differences cannot completely be excluded, however. As the discrimination criterion was again high-low, pitch orderings can be correctly made for the AM-tones based on the periodicity of the waveform which corroborates the results of the previous experiment.

CHAPTER 6

PSYCHOPHYSICAL TUNING CURVES

6.1 Introduction

In the previous chapter it was shown that for hearing impaired listeners frequency discrimination curves may be found that deviate strongly from the normal curve. Based on the observations and deductions for normal hearing listeners it was concluded that for the most deviating curves the frequency analyzing capacity at the corresponding filter frequency had to be rather poor. The derivation of an equivalent bandwidth of the auditory filter on the basis of the shape of the frequency discrimination curve would be too complicated. Therefore the frequency analyzing capacities of hearing impaired listeners will be investigated in this chapter by other means. We will focus our attention on psychophysical tuning curves.

Psychophysical tuning curves were first reported in the literature by Small (1959). Recently the method got renewed attention (Vogten, 1974; Zwicker, 1974). Psychophysical tuning curves are comparable to 8th nerve fibre tuning curves and are therefore assumed to reflect many of the properties of pheripheral auditory frequency selectivity at the probe tone frequency. Actually, they represent the levels of a variable tone just masking a faint probe tone as a function of frequency. Loss of frequency analyzing capacity will be reflected in the psychophysical tuning curve.
For the same hearing impaired subject psychophysical tuning curves and frequency discrimination results will be compared.

6.2 Experiments

The procedure used for the determination of a psychophysical tuning curve is described in chapter 2. It is essentially a direct masking method in which the confounding effects of probe-masker interactions have been minimized. Effects of lateral suppression are still involved and should be borne in mind in interpretating the results.
Fig. 6.1 shows some examples of psychophysical tuning curves found for normal hearing listeners with our particular experimental paradigm. A few curves with a probe tone level of more than 10 dB are included, with and without additional masking

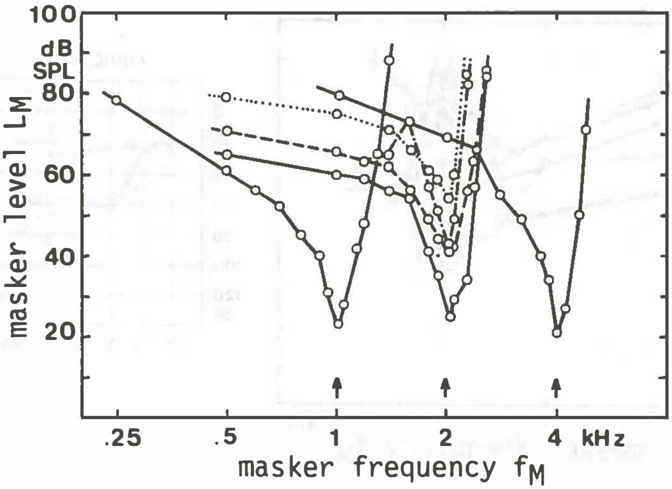
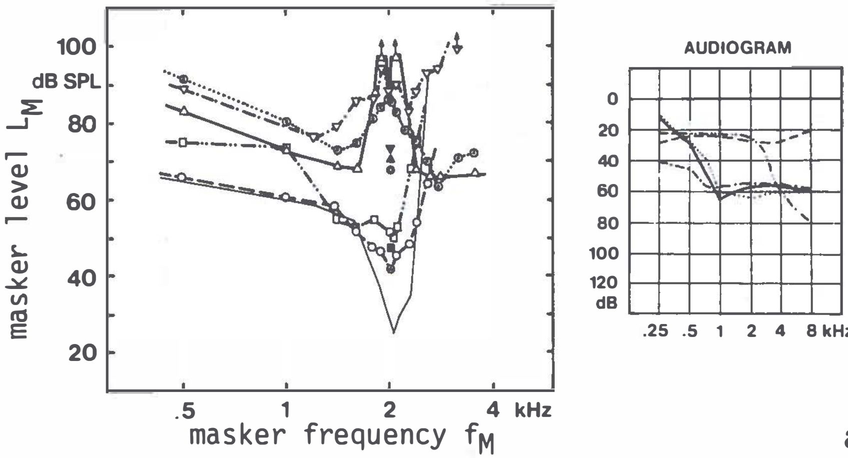


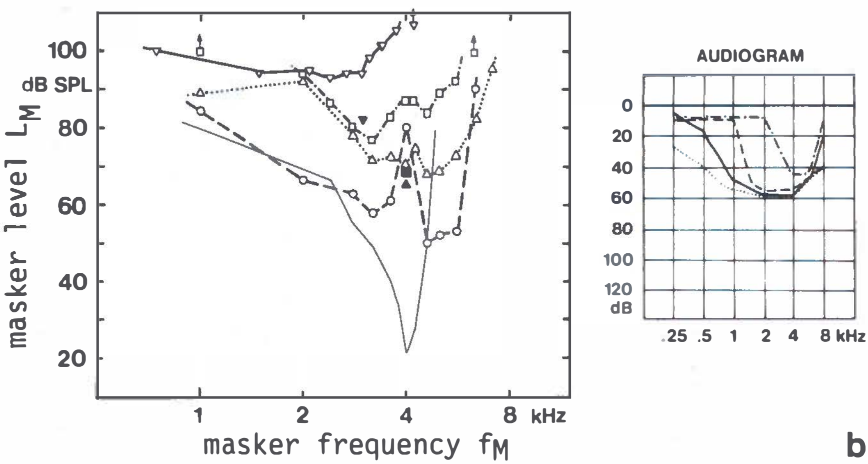
Fig. 6.1 Psychophysical tuning curves for one normal hearing subject (AH). The frequencies of the test tones (1,2 and 4 kHz) have been indicated by arrows.
Solid line: L_T = 10 dB SPL.
Dash-dotted line: L_T = 30 dB SPL.
Dashed line: L_T = 30 dB SPL, a continuous LP-noise is added (f_{co} = 0.5 kHz; attenuation rate: 24 dB/oct; masking level of the noise: 50 dB SPL).
Dotted line: L_T = 43 SPL (5 dB SL), a contiuous broad-band noise is added (masking level of the noise: 38 dB SPL).
The influence of combination tones on the shape of the psychophysical tuning curve can be seen in the dash-dotted curve: notch around f_M = 1.6 kHz.

noise. Without masking noise the curve shows a notch for $f_M < f_T$ as a result of the detection of combination tones (see Greenwood, 1971). Adding LP-noise (f_{co} = 0.5 kHz; 24 dB/oct roll-off and masking value equal to 50 dB SPL) the combination tones are masked and the notch vanishes. Broad-band noise does not affect the shape of the psychophysical tuning curve appreciably. The sharp tip is clearly maintained, while the whole curve is shifted to higher levels.

Psychophysical tuning curves for hearing impaired subjects can be quite different from those of normal hearing listeners. This may be seen from fig. 6.2. Generally, the loss of the tip of the tuning curve is the first thing to occur. With increasing hearing loss the tip gradually disappears and is complete-



a.



b.

Fig. 6.2 Psychophysical tuning curves for hearing impaired listeners. The thin solid line is the normal curve from fig. 6.1. The corresponding pure tone audiograms are given on the right. Black symbols indicate the respective f_T and L_T.

a. f_T = 2 kHz — -○- - *D.R.* ♀ *64* ····⊙···· *J.K.* ♂ *17*
···□··· *J.vdW.* ♂ *46* -·▽·- *I.B.* ♀ *15*
—△— *A.V.* ♀ *14*

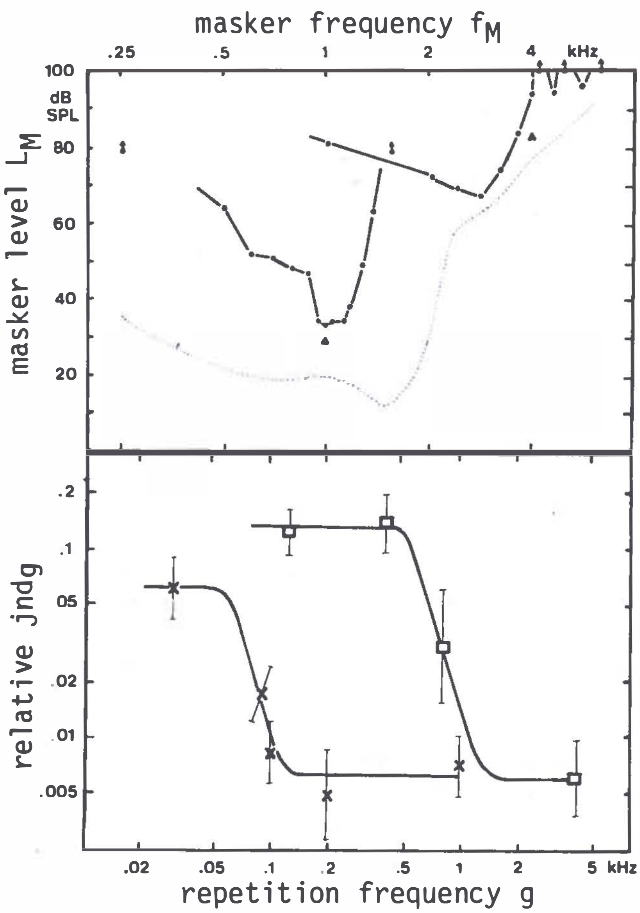
b. f_T = 3 kHz —▽— *H.B.* ♂ *66*
f_T = 4 kHz - -○- - *J.D.* ♂ *56* -··□··- *D.T.* ♂ *28*
·····△···· *G.B.* ♀ *14*

ly gone for hearing losses greater than about 40 dB. In many cases also the shape of the tuning curve alters drastically: w-shape patterns were found, patterns with excessive downward spread of masking and other irregular shapes. These deviations were observed for hearing losses greater than 40 dB. The shape of the tuning curve is not uniquely related to the magnitude of the hearing loss at the probe tone frequency. The course of the threshold elevation as a function of frequency is important; in other words the masking result is not only determined by $|f_M - f_T|$, but is also influenced by the difference in threshold elevation at f_M and f_T.
In case of a w-shaped tuning curve the masking of the probe tone is maximal for masker-frequencies $f_M \sim f_T \pm \frac{1}{2}$ octave. In the immediate vicinity of the probe tone masking is minimal. In contrast, for normal hearing listeners masking is always maximal for $f_M \sim f_T$, even at the high probe tone levels that have to be used for hearing impaired listeners to compensate for their threshold elevation.
The large spread of masking towards low masker tone frequencies was expected and is often comparable to the findings with normal hearing listeners. A striking unexpected feature of the curves is, apart from the notching around f_T, the considerable masking for $f_M > f_T$, extending sometimes to one octave above f_T (figs. 6.2a JK, AV; 6.2b JD, GB; 6.4 and 6.7). This downward spread of masking ($f_M > f_T$) is also found in non-w-shaped tuning curves (fig. 6.2b GB).
Another feature that can be seen in the figures is that tones of a lower intensity than the probe tone may be effective maskers (figs. 6.2b, JD; 6.3 and 6.7). The difference between probe tone and masker tone level can be as large as 15 to 20 dB. The effect is observed both on the high- and the low-frequency side of the probe tone.
The curves are sometimes quite irregular in the vicinity of f_T, with narrow local masking maxima at $f_M \sim f_T$ (fig. 6.2a AV).

No evidence has been found for the occurence of combination tones in the psychophysical tuning curves of the hearing impaired listeners. Notches in the region around $f_T/f_M \sim 1.3$ (the best ratio for hearing combination tones) have not been observed. Admittedly, low-pass masking noise was present during the determination of the tuning curves ($f_{co}=f_T/4$; roll off: 24 dB/oct). The aim of the addition of noise was to mask the otherwise possibly audible difference tones. Interference with the audibility of combination tones cannot completely be excluded, but the moderate level of the noise makes this unlikely. We should rather expect that cubic combination tones are not generated when the primaries are situated well within the lesion.

6.3 Comparison of psychophysical tuning curves and frequency discrimination data.

After this more general description of the psychophysical tuning curves obtained with hearing impaired listeners, we come to our particular aim, viz. the comparison between the frequency discriminaion ability and the shape of the tuning curve in the same frequency region.
In most cases the frequency discrimination data and the psychophysical tuning curves concur. Deviating frequency discrimination curves are always accompanied by abnormal tuning curves.



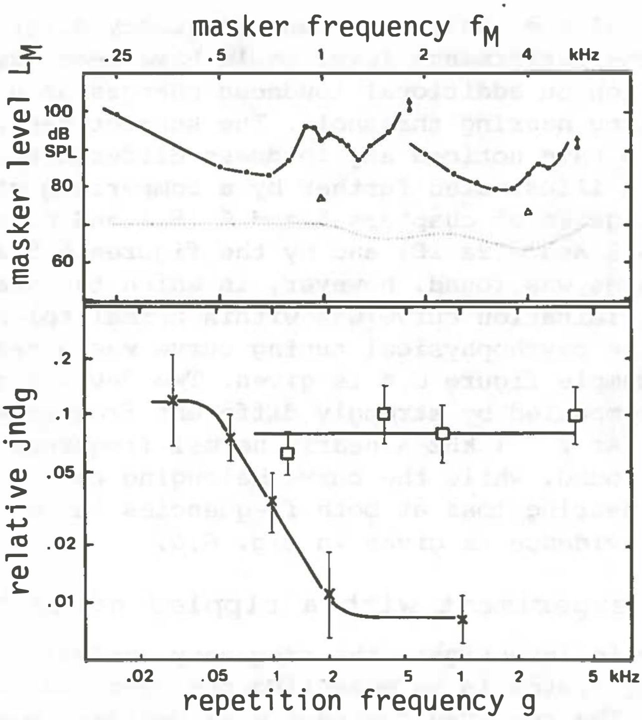


Fig. 6.4 Same as fig. 6.3, but for another hearing impaired subject. (M.S. ♀ age: 15).

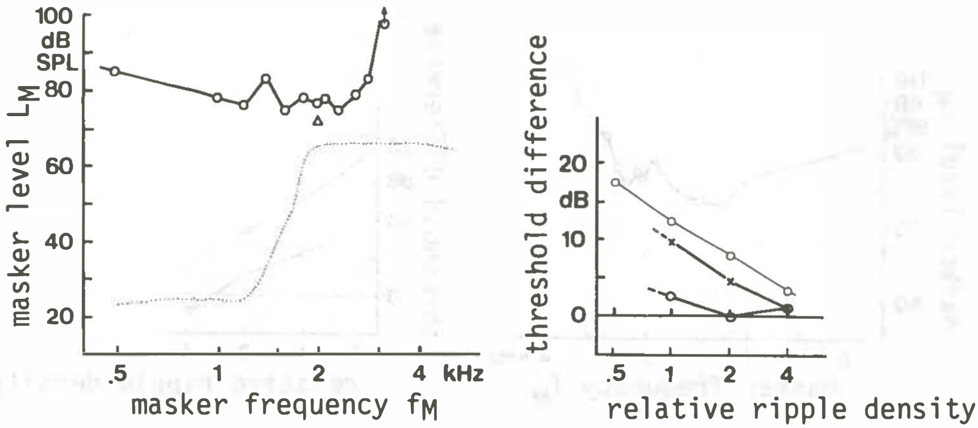
Accordingly, with a normal tuning curve frequency discrimination is good. This may be illustrated by the results of a subject with an abrupt high frequency hearing loss (fig. 6.3). At f = 1 kHz where the hearing loss is very slight, a normal frequency discrimination curve is found. The tuning curve at this frequency is also almost normal, though with a somewhat blunt tip. At f = 4 kHz there exists a hearing loss of about 70 dB and the tuning curve is abnormal. The frequency discrimination

Fig. 6.3 Frequency discrimination data and psychophysical tuning curves for the same hearing impaired subject. (M.P. ♀ age:15). Upper part: Psychophysical tuning curves for f_T = 1 kHz and 4 kHz. The triangle indicates the frequency and level of the probe tone. The dotted line represents the hearing threshold. Lower part: The relative jnd$_g$ as a function of the repetition frequency. × *: f = 1 kHz ;* □ *: f = 4 kHz.*

curve is abnormal too. Only pure tone frequency discrimination is good, but the performance level could have been exaggerated by discrimination on additional loudness changes as a consequence of the sloping hearing threshold. The subject reported, however, not to have noticed any loudness differences. The concurrence may be illustrated further by a comparison of some of the previous figures of chapters 5 and 6 (5.1 and 6.2a JK; 5.5 and 6.2b GB; 5.6 and 6.2a IB) and by the figures 6.5 and 6.7.
A number of cases was found, however, in which the shape of the frequency discrimination curve was within normal tolerance limits while the psychophysical tuning curve was already aberrant. As an example figure 6.4 is given. Two deviating tuning curves are accompanied by strongly different frequency discrimination data. At f = 1 kHz a nearly normal frequency discrimination curve is found, while the curve belonging to f = 4 kHz is abnormal. The hearing loss at both frequencies is nearly the same. Further evidence is given in fig. 6.6.

6.4 Masking experiment with a rippled noise masker

Another way to investigate the frequency analyzing capacity of the auditory system is by measuring the resolved contrast in rippled noise. The resolved contrast will decrease when the ripple spacing is made progressively finer. The essentials of this experiment have been described in chapter 2. The results of the experiment are expressed in the resolved contrast (i.e. the masking level difference between probe-tone-in-peak and probe-tone-in-valley) as a function of the relative ripple density $f_T/\Delta f$ (i.e. the number of noise peaks between f = 0 and the probe tone frequency $f = f_T$; $1/\Delta f$ is the ripple density, i.e. the number of noise peaks per unit frequency). From these data a hypothetical filtercharacteristic can be calculated. The bandwidth of this calculated filter serves as a measure of the frequency selectivity at the probe tone frequency. Details of the involved calculations can be found in Houtgast (1974).
The results for a small number of normal hearing listeners obtained at f = 2 kHz (L_T = 40 dB SL) served as a reference. These results are included in figures 6.5 to 6.7. The obtained values for the resolved contrasts of normal hearing listeners are in agreement with those reported in the literature (Houtgast, 1974; Pick et al., 1977). The resolved contrast decreases with increasing relative ripple density.



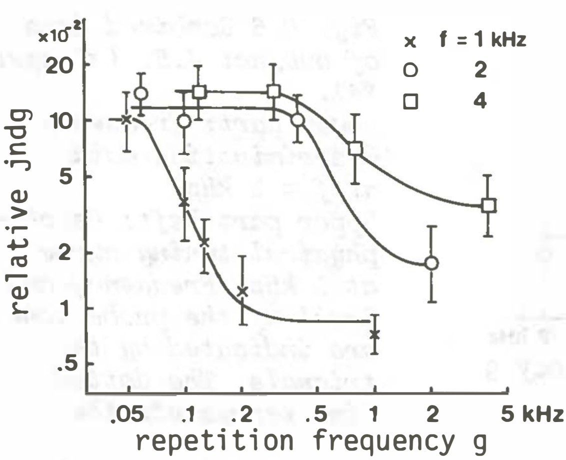
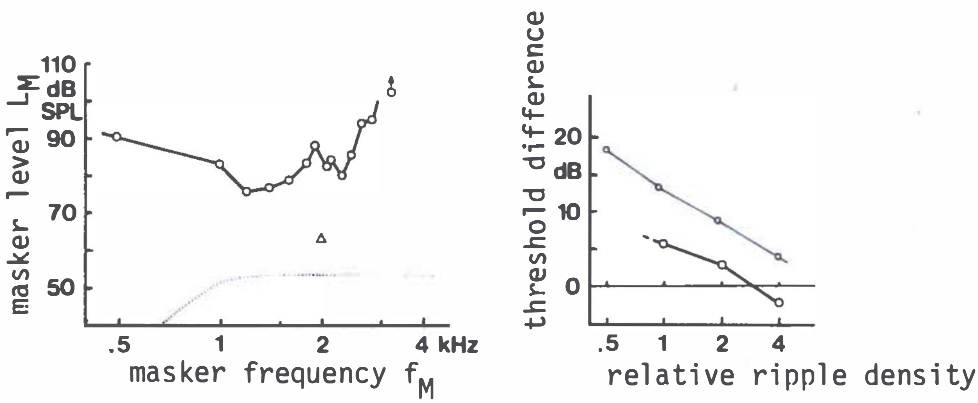


Fig. 6.5 Combined data for subject T.C. (♂ age: 61).
Lower part: Frequency discrimination data for three filter frequencies.
Upper part left: Psychophysical tuning curve for f_T = 2 kHz. The triangle indicates the frequency and level of the probe tone. The dotted curve represents the hearing threshold.
Upper part right: The resolved contrast in a rippled noise masker as a function of the relative ripple density. ×: f_T = 1 kHz, L_T = 40 dB SL; ○ : f_T = 2 kHz, L_T = 20 dB SL. The averaged data for normal hearing listeners are indicated by the thin line.

For hearing impaired listeners resolved contrasts were measured at f_T = 1 kHz and 2 kHz. The level of the probe tone was fixed between 10 and 40 dB SL, depending on the amount of the hearing loss. Some of the results are shown in fig. 6.5 and 6.7. Hearing impaired listeners (6 more were examined than the 3 shown) show a considerably lower resolved contrast than normal hearing listeners. The difference becomes negligible for small hearing losses (see fig. 6.5 f_T = 1 kHz). The range of hearing



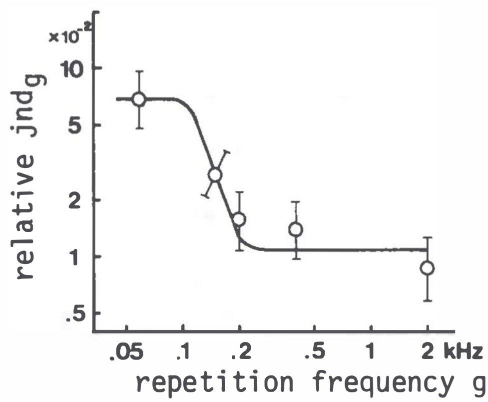
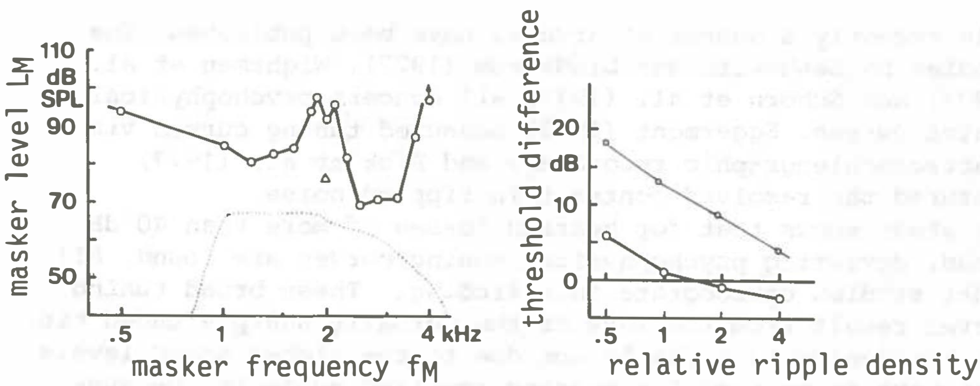


Fig. 6.6 Combined data of subject J.B. (♂ age: 24).
Lower part: Frequency discrimination data at f = 2 kHz.
Upper part left: Psycho-physical tuning curve at 2 kHz. Frequency and level of the probe tone are indicated by the triangle. The dotted line represents the hearing threshold.
Upper part right: Resolved contrast in a rippled noise masker. f_T = 2 kHz, L_T = 20 dB SL. Thin line: normal results.

loss covered and the number of subjects were too small to confirm a correlation between hearing loss and resolved contrast. From the last three figures it can be extracted that a qualitative correspondence exists between the resolved contrast and the deterioration of the tuning curve. The size of the measuring error prevents a more quantitative comparison through the calculation of an equivalent filter. It is unwarranted to derive a general relationship between frequency discrimination curves and rippled noise masking data based on these few measuring results.



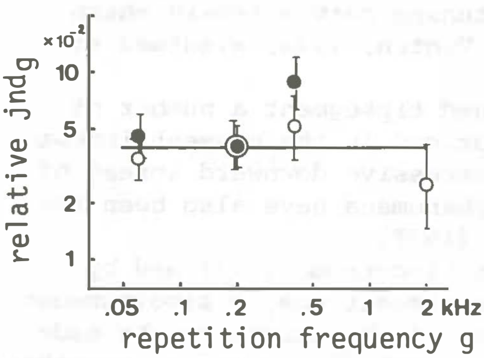


Fig.6.7 Combined data of subject P.vd S. (♂ age:21). Lower part: Frequency discrimination data at $f = 2$ kHz. Open symbols: slope steepness of the 1/3-octave bandfilter 100 dB/oct. Closed symbols: slope steepness of the bandfilter 50 dB/oct. Upper part left: Psychophysical tuning curve at 2 kHz. Frequency and level of the probe tone are indicated by the triangle. The dotted line represents the hearing threshold. Upper part right: Resolved contrast in a rippled noise masker. f_T = 2 kHz, L_T = 10 dB SL. Thin line: normal results.

6.5 Discussion

The psychophysical tuning curves, considered to be a direct reflection of the frequency selectivity of the auditory system at the probe tone frequency, are in complete agreement with the literature for normal hearing listeners (see fig. 6.1 and for instance Houtgast, 1974; Rodenburg et al., 1974; Vogten, 1974 and Zwicker, 1974). The measured effects at probe tone levels of more than 10 dB and with addition of noise are in agreement with the psychophysical results of Zwicker (1974) and also with the electrophysiological results obtained by Kiang and Moxon (1973).

When this study was started little precise data existed about the frequency resolution of hearing impaired listeners.

Only recently a number of studies have been published. The studies by Leshowitz and Lindstrom (1977), Wightman et al. (1977) and Schorn et al. (1977) all concern psychophysical tuning curves. Eggermont (1977) measured tuning curves via electrocochleographic recordings and Pick et al. (1977) measured the resolved contrast in rippled noise.
Our study shows that for hearing losses of more than 40 dB broad, deviating psychophysical tuning curves are found. All other studies corroborate this finding. These broad tuning curves result from the loss of the normally sharply tuned tip. The broadening is probably not due to the higher sound levels that have to be used for hearing impaired subjects, because for normal hearing listeners the tuning curves remain sharp at higher probe levels (fig. 6.1; Vogten, 1974; Wightman et al., 1977).
Beyond the loss of the sharply tuned tipsegment a number of striking abnormalities has been noticed in the present investigation: w-shaped tuning curves, excessive downward spread of masking and "overmasking". These phenomena have also been reported by Leshowitz and Lindstrom (1977).

In the studies by Leshowitz and Lindstrom (1977) and by Schorn et al. (1977), alike in the present one, a simultaneous masking paradigm was used. A number of objections can be made against this method of simultaneous masking because of possible probe-masker interactions. Therefore, Wightman et al. (1977) studied psychophysical tuning curves both for normal hearing and hearing impaired listeners with a simultaneous as well as a non-simultaneous masking paradigm. For normal hearing listeners there is a considerable difference in the results of both methods. This difference is attributed to the influence of suppression effects in the simultaneous masking condition. On the contrary, the tuning curves for the hearing impaired listeners nearly superimpose in both conditions when the probe tone is located at frequencies at which a hearing loss exists (Wightman et al., 1977). It was confirmed by them in additional suppression measurements, that hearing impaired listeners exhibit no lateral suppression at the frequency of the hearing loss. The same conclusion is drawn by Leshowitz and Lindstrom (1977): absence of lateral suppression is a concomitant of abnormal frequency selectivity. Leshowitz reported orally at the Keele-Symposium (Evans and Wilson, 1977) about the differences in psychophysical tuning curves with either a simultaneous or a non-simultaneous masking procedure. This is especially interesting in the case of a w-shaped tuning curve. The notch at the probe tone frequency seems to disappear while the width of the tuning curve does not change appreciably. This finding makes it plausible that the notch in the tuning curve results from a probe-masker interaction. This probe-masker interaction is not audible for normal hearing listeners, judging from the fact that these notches are not found in psychophysical tuning curves of normal hearing listeners. Simple detection of beats or of interference effects cannot therefore explain the release of masking around the probe tone frequency. A possible explanation was put forward by Viemeister (in Evans and Wilson, 1977, pg. 293). He relates the shape of the notch to the low-pass characteristic of the modulation transfer function of the ear (see Rodenburg, 1977 and Viemeister, 1977). The assumption is made that the hearing impaired listener detects some kind of beats due to his deteriorated frequency resolution in that frequency region. The beat frequency decreases as the masker tone frequency approaches the probe tone frequency and, in accordance with the modulation transfer function, a raise in masking level is required to make the modulation inaudible. For the most clear and regular notches the slope varies from 6 to 12 dB/oct in our material. This is higher than the attenuation rate of the normal modulation transfer function. Most authors (Rodenburg, 1972; Buunen, 1976; Green, 1973) agree to the value of 6 dB/oct, while Viemeister (1977) claims 4 dB/oct. The reason for these differences is not clear at present. Modulation transfer functions for hearing impaired listeners have not yet been published. The explanation of the notch by "beat" detection corresponds somehow with the subjective reactions of some listeners. They perceived the probe tone somewhat like the plucking of an electrical guitar (remember that we used two short probe tones in succession).

Threshold elevation leads to a progressive loss of the sharply tuned tip of the psychophysical tuning curve. This results inevitably in increased upward spread of masking ($f_M < f_T$). The slope of the tuning curve towards lower frequencies is the same as the slope of the tail of the normal tuning curve in most cases. More intriguing is the often observed excessive downward spread of masking ($f_M > f_T$)(see figs. 6.2 and 6.7). We do not have an explanation for this phenomenon, nor is the recent literature helpful in this respect. More research is needed.

In figs. 6.2, 6.3 and 6.7 examples of the phenomenon of "overmasking" can be seen: a masker tone of lower intensity than the probe tone is able to mask that probe tone. According to Leshowitz and Lindstrom (1977) "overmasking" has been observed in almost all listeners having an abrupt high frequency hearing loss. Differences in threshold elevation at f_M and f_T probably influence the shape of the tuning curves. This cannot be the only reason as is apparent from fig. 6.2. The phenomenon of "overmasking" may also be related to the hypersensitivity of the tails of physiological tuning curves sometimes seen in damaged neural units in case of acoustic trauma (Kiang et al., 1976). It was found by Kiang et al. that the effects of cochlear damage need not be limited to loss of responsiveness in the nerve fibre, but that abnormal units can respond actively to stimuli that were subthreshold before the injury. These hypersensitive tails are often seen together with hyposensitive tips (Kiang et al., 1976; Dallos et al., 1977) so that w-shaped tuning curves result. Although this seems to point to a close parallel between the psychophysical and the physiological tuning curve, the interpretation of both w-shapes is different. The characteristic frequency (CF) of the physiological tuning curves of the w-type is thought to be at the elevated tip segment, whereas in the psychophysical tuning curve the probe tone frequency is situated right in the middle of the notch. The presence of the above mentioned abnormal units will make the psychophysical tuning curve difficult to interprete.

If in spite of the above mentioned reservations the psychophysical tuning curves for hearing impaired listeners still bear resemblance to single unit tuning curves from damaged cochleas, then what might be inferred about the presence or absence of haircells? Kiang et al. (1976) found that in regions devoid of outer haircells there is a gap in the range of assignable CF's of a tuning curve for cats. Dallos et al. (1977) maintain, however, that even in regions where all outer haircells are missing sharp tips can be found in the tuning curve which determine its CF. Their results pertain to chinchillas. Harrison and Evans (1977) and Evans (1975) conclude that for guinea pigs different types of cochlear pathology that result in complete loss of outer haircells with apparently intact inner haircells, lead to tuning curves that are very broad (the $Q_{10\ dB}$ of nerve fibres from abnormal cochleas varies from 1 to 2 whereas the normal range is from 3 to 10). Despite these differences in opinion about the effect of outer haircell loss upon the tuning curves it can be deduced from the literature that a significant haircell loss is always accompanied with a drastic threshold shift of the tip and a change of the shape of the tuning curves. The tail is often unchanged, but may become hypersensitive. Damage to the inner haircells with intact outer haircells seems to result in a loss of sensitivity in both the tip and tail (Kiang et al., 1976). On the other hand when tuning curves appear normal or have an easily assignable CF in a certain frequency region there will be no extensive haircell loss (Kiang et al.,1976). Still, threshold shifts of the tuning curve tip may be found in regions with virtually no haircell loss. The mere presence of haircells tells nothing about their integrity. Refined techniques have to be awaited that may record more subtle functional abnormalities then just complete absence of haircells. Therefore, the degree of abnormality of a tuning curve can only give a rough indication of the underlying haircell losses. This applies with greater force to psychophysical tuning curves. It is quite conceivable that different configurations of haircell loss might yield virtually the same psychophysical tuning curve.

Because of its analogy with single unit tuning curves the psychophysical tuning curve is considered to be the reflection of peripheral frequency selectivity. In the previous chapter it was argued that loss of frequency resolution is expressed in the frequency discrimination data of bandfiltered periodic pulse trains. It is reasonable to expect that the outcome of both experiments concurs for the same hearing impaired listeners. To make a proper comparison, the frequency discrimination data would have to be translated into an equivalent auditory filter bandwidth. This was found to be unfeasible. But it is also for psychophysical tuning curves difficult to decide what the bandwidth actually is, e.g. with a w-shaped tuning curve. So the comparison has to remain qualitative.

If we assume that a progressive loss of frequency resolution appears in the frequency discrimination data as the deterioration of the clear sigmoid shape of the characteristic frequency discrimination curve into a straight line, and in psychophysical tuning curves as the loss of the sharp tip or worse, the more irregular shapes, then there is usually agreement between both measures of frequency resolution. There are,however, cases in which the psychophysical tuning curve is already deteriorated while the frequency discrimination data are still rather good.

Effects of lateral suppression can be disposed of as an argument to reconcile these conflicting data, because Leshowitz and Lindstrom (1977) and Wightman et al. (1977) have shown that the mechanism of lateral suppression is rendered inoperative in regions of notable hearing loss. Obviously the psychophysical tuning curve exhibits effects of probe-masker interactions (e.g. the w-shape), which may partly explain the observed differences. Dallos et al. (1977) have measured psychophysical tuning curves and physiological tuning curves in chinchillas in one and the same animal. They found clear differences between both. They assume that in psychophysical tuning curves also mechanisms beyond the eight nerve level are involved. Regarding the above it may be questioned whether in cases of pathology the psychophysical tuning curve is indeed the simple reflection of frequency selectivity it is assumed to be. We must confine ourselves to note that presumably we are confronted with two different expressions of the same fundamental property of the auditory system, i.e. of the frequency analyzing capacity, which expressions usually concur, but may differ.

CHAPTER 7

FINAL DISCUSSION

7.1 On the mechanism of frequency discrimination in relation to frequency analysis

There are two ways in which the frequency content of a sound can be coded: by the temporal pattern of the discharges in the 8th nerve fibres and by the distribution of activity among different fibres. As a consequence of the specific structure of the cochlea frequency is spatially distributed along the basilar membrane. The auditory nerve fibres are evenly distributed along the cochlear partition, so that different groups of nerve fibres will respond to different frequencies. The spectrum of a stimulus will be reflected in the distribution pattern of mean firing rate in the bundle of nerve fibres. The spatial distribution of mean firing rate on the nerve fibre array is retained towards higher stations of the auditory pathway due to the tonotopical organisation of at least the lower part of this pathway. On the other hand the spatially distributed activity is also structured temporally. Up to 5 kHz the nervous discharges have been shown to be phase-locked to tonal stimuli (e.g. Kiang, 1965; Rose, 1971).
The discharge pattern of a single nerve fibre will resemble a filtered version of the waveform of the stimulus. Depending on the degree of frequency resolution and stimulus composition some nerve fibres will show activity which is synchronized to the periodicity of an individual harmonic, while others will exhibit an activity pattern related to the combined action of a number of harmonics in response to the stimulation with a periodic complex tone. It is a topic of controversy whether changes in the mean time integrated firing rate of a small group of nerve fibres determines the frequency discrimination of a pure tone or that changes in the fine time structure of neural discharges are essential.

Different models have been proposed to account for the jnd's in frequency of pure tones. These range from purely psychophysical to purely physiological models. Psychophysical models may be afterwards related to facts of neurophysiology, physiological models need to be tested by comparison of their estimates of discrimination accuracy with available psychophysical data. For pure tones efficiently processing of the mean discharge rate seems to be adequate to describe the observed psychophysical precision (Siebert, 1968; 1970). Even the phenomenon of saturation of neural discharge rate at higher SPL's need not interfere with a discrimination mechanism based upon changes in mean discharge rate, because some unsaturated nerve fibres will always be available at the borders of the activity pattern. For the complex tones as used in this study a discrimination mechanism based on detection of changes in neural discharge rate seems to be inadequate, especially at higher sound levels. Now, the neurons on the borders of the activity pattern will not provide the necessary information. It will be suspected that detailed timing information is then indispensable. We suggest that the frequency discrimination data for the complex tones used in this study can be described on the basis of efficient processing of interspike intervals. Although the results from Siebert's (1970) study suggest that periodicity information in the discharge pattern of primary fibres can be ignored, Goldstein (1977) has shown that processing of interspike intervals can predict adequately the behavioural limits of frequency discrimination of pure tones.

As said before the cochlear filtering process plays a far from negligible role in the production of the temporal fine structure; it prepares the complex tone for temporal processing by preventing interference between adjacent harmonics as much as possible. In chapter 3 it was argued that the jnd in repetition frequency of a bandfiltered periodic pulse train depends on the degree to which the constituting frequency components can be analyzed spectrally. With resolved harmonics different neural channels will carry a different fine time structure and frequency discrimination is then optimal. When complete resolution is not feasible anymore the difference in the discharge patterns of different nerve fibres will disappear gradually. Ultimately the only relevant peak remaining is the interval histogram of all channels will be the one corresponding to the period of the complex tone. Frequency discrimination remains then at a constant level: the rattle region.

When non-overlapping frequency spectra, as used in section 3.4, are concerned the temporal information of the independent neural channels has to be processed to estimate the pitch of the complex tone prior to pitch discrimination. The absolute value of the jnd_g increases thereby, but the interrelations remain intact (fig. 3.8). An increase in jnd_g when pitch discrimination is concerned,is in accordance with Goldstein's pitch theory (1973): the precision with which the frequency information is conveyed to the central processor of pitch is poorer than the precision encountered in pure tone frequency discrimination. Goldstein does not specify the precise form of the input to the central pitch processor: "place" or "time". Recently he has announced a central spectrum model on auditory nerve interval information (Goldstein, 1977).

Though frequency discrimination is no doubt not a peripheral process, the ability to detect a change in frequency is altered by a lesion in the cochlea. Frequency discrimination of pure tones as well as complex tones is generally worse than normal with a cochlear hearing loss. Under pathological conditions of the cochlea the cochlear nerve tuning deteriorates (see chapter 6). How timing properties are affected has not been very well documented up till now. Alterations in the distribution of spontaneous rate have been shown (Kiang et al., 1976). Data concerning phase-locking are not available yet. In normal cochlear nerve fibres phase-locking of discharges to the stimulus periodicity have been shown to exist up to 5 kHz (Rose et al., 1971). It is conceivable that this limit is lowered in case of cochlear pathology. The fact that a normal frequency discrimination curve is less likely to be found for higher filter frequencies is then compatible with a temporal model of frequency discrimination.

Deteriorated tuning will prevent the locking of neural discharges to one particular frequency component of the stimulus. The situation in which only the period of the stimulus is clearly represented in the interspike interval histogram is then attained already for higher repetition frequencies, resulting in a flat frequency discrimination curve.

For pure tones frequency discrimination on the basis of a "place" principle is still a reasonable possibility. It is then important whether the deterioration in tuning properties is symmetrically or not. For a frequency discrimination mechanism based on shifts in excitation pattern ("place" model), especially the steepness of the low frequency slope is important. For a good frequency analysis and a frequency discrimination mechanism that is based thereon, a steep high frequency slope is needed additionally. For many hearing impaired listeners we have found strongly asymmetrical psychophysical tuning curves. In these cases the frequency discrimination of a pure tone could be rather good as compared to the results of the

frequency discrimination of the repetition frequency of band-filtered periodic pulse trains, for which good frequency analysis is required. This is actually observed in the experimental data. This interpretation of the data makes the exceptional position of the pure tone understandable. Consequently, pure tone frequency discrimination is not likely to be a good predictor of the frequency analyzing capacity of a subject.
The mean difference in jnd for frequency of a pure tone between untrained normal and hearing impaired listeners could, irrespective of the discrimination mechanism involved, be the result of the fact that fewer viable nerve fibres are available.

7.2 Final remarks and conclusions

When this study was started it was generally conjectured that it is the frequency analyzing capacity that has been disturbed in case of cochlear malfunctioning, but surprisingly little was really known about the pathology of this fundamental property of the auditory system. We have tried to get a better insight in the analytic and discriminative capacities of perceptively hearing impaired listeners by means of a number of different experiments as described in the previous chapters. We adopted as our working hypothesis that the frequency analyzing capacity of the auditory system can be revealed by means of frequency discrimination experiments with complex tones (i.e. with bandfiltered periodic pulse trains). In this way the measurement of both faculties was combined in one experiment. This hypothesis appeared to be fruitful.
In the experiments of chapter 3 it was found for normal hearing listeners that a very characteristic frequency discrimination curve exists for bandfiltered periodic pulse trains when the relative jnd in repetition frequency is plotted against the harmonic number $n = f/g$. This curve consists of two plateaus of constant discrimination level with a transition region in between. The shape of the curve is not significantly influenced by a number of changes in the filtercharacteristic or by the addition of LP-noise. The combined data are interpreted as a corroboration of the hypothesis that the frequency analyzing capacity shows up in the frequency discrimination data of band-filtered periodic pulse trains.
On the basis of this knowledge the frequency discrimination data of hearing impaired listeners, usually strongly deviating from those of normal hearing listeners, can be explained as a manifestation of a deteriorated frequency analyzing capacity. The

conclusions about the frequency analyzing capacity have to remain qualitative without the availability of a suitable model to derive a filter bandwidth from the frequency discrimination data. Therefore psychophysical tuning curves have been measured for the same hearing impaired listeners. The psychophysical tuning curves obtained in frequency regions of hearing loss show a considerable variation, ranging from a blunting of the sharp tip to an alteration of the tuning curve into a w-shape. Overmasking and excessive downward spread of masking are other notable findings. Many of these findings are corroborated by other recent publications (see chapter 6).
The frequency discrimination data and the psychophysical tuning curves can be related and show a considerable agreement in terms of frequency analysis. The presumed relation between a cochlear hearing loss and a deterioration of the frequency analyzing capacity is amply confirmed.

During the investigation the results of working with hearing impaired listeners have proved to be remarkably unpredictable. Even such a seemingly straightforward function as the psychophysical tuning curve appears to be highly complicated and must be very carefully interpreted for hearing impaired listeners. Generalizations are less easy to make for hearing impaired listeners than for normal hearing listeners. Though average trends may be clear, for instance the jnd_f as a function of hearing loss, individual deviations are often considerable, which makes predictions of individual data from the average data idle. For the same reason no strict borderline can be drawn between normal and pathological, though the average data are significantly worse compared with normal.

The frequency discrimination data and the shape of the psychophysical tuning curve cannot be predicted for a particular hearing impaired individual from the audiological data routinely obtained in clinical practice. Enlargement of the test battery with tests concerning the frequency analyzing capacity will be helpful to obtain a more complete picture of the consequence of a hearing impairment.

The number of speech intelligibility tests has been deliberately limited in this study. Consequently, the few data are inconclusive regarding the relation between frequency discrimination and speech intelligibility, though some support for a correlation was found when HP-filtered speech words were used. Speech perception involves much more than only discrimination of frequencies; still, it is hard to avoid the idea that a deteriorated frequency analyzing capacity is detrimental to speech intelligibility.

As noted already in the introduction a deteriorated frequency analyzing capacity combined with the observed abnormal spread of masking, will reduce the possibility to detect changes in the spectral composition of auditory stimuli necessary for adequate speech processing. To circumvent these problems future hearing aids will have to process incoming signals in such a way that the auditory system is able to analyse individual frequency components relatively free of undesirable interactions. This might be accomplished by some kind of prefiltering, so that adjacent parts of the frequency spectrum are presented to each ear, relying on central fusion to recombine the dichotic information (Danaher and Pickett, 1975; Evans, 1975; 1978).

Investigations of the properties of the malfunctioning auditory system provides a wealth of new questions, which are worth considering in view of the often enormous problems arising from a hearing handicap. This more extensive knowledge of the physiological and psycho-acoustical aspects of hearing impairment is a prerequisite for a possible compensation of a hearing defect. It is hoped that this study has contributed to this end.

SUMMARY

Frequency discrimination and frequency analysis are two distinct abilities of the auditory system. Frequency discrimination is the ability to distinguish between non-simultaneous tones as regards their frequency, whereas frequency analysis is the ability to analyse a sound into its components. Frequency analysis is chiefly determined by the properties of the auditory filter, which is assumed to be situated in the inner ear. For normal hearing subjects both capacities have been investigated fairly minutely. For hearing impaired persons only frequency discrimination has received some attention until recently. It is generally supposed that in case of a perceptive hearing loss of cochlear origin the frequency analyzing capacity has decreased. At the time the present study was started exact data were scarce, especially regarding the relations with other consequences of a perceptive hearing loss. For instance, it is plausible that a good frequency analyzing capacity is required for a good speech intelligibility particularly under unfavourable circumstances. In the present study an attempt has been made to contribute to a better insight into the discriminating and analyzing capacities of the pathological hearing organ. For this purpose frequency discrimination experiments have been performed and so-called psychophysical tuning curves have been determined.

By using stimuli consisting of a group of higher harmonics, frequency discrimination can be related to frequency analysis. In this investigation the just noticeable difference in repetition frequency (jnd_g) of bandfiltered periodic pulse trains is determined. The degree to which the constituting harmonics of this signal can be analyzed is dependent on the relation between the repetition frequency and the filter frequency, among other things.

In chapter 3 a detailed investigation is described, with a limited number of trained, normal hearing subjects, to see to what degree and in what way the limited frequency analyzing capacity of the peripheral auditory system is reflected in the results of the frequency discrimination experiment. It appears there is a characteristic relation between the relative jnd_g on the one hand and the repetition frequency g on the other hand: a curve consisting of two plateaus of a constant, but among themselves strongly different discrimination level with a transition region in between. Changes in the filter charac-

teristic, such as a bandwidth variation of 1/3- to 1/1-octave and changes in the slope steepness of 50 to 150 dB/oct., have little or no influence on the characteristic curve. However, for very steeply sloping filters the relative jnd_g becomes almost independent of the repetition frequency. The adding of noise has an unfavourable influence on the frequency discrimination capacity. The increase of the jnd_g with decreasing signal-to-noise ratio appears to have a different course for stimuli with a low harmonic number n (n = f/g) than for stimuli with a high harmonic number. The transition is approximately at n = 14. When the pulse trains to be compared are fed into bandfilters tuned to different frequencies, so that distinction is only possible by pitch comparison, a similar frequency discrimination curve as mentioned above is found. The conclusion from the data obtained is that the shape of the characteristic frequency discrimination curve is determined largely by the limited frequency analyzing capacity of the hearing organ: as long as the constituting harmonics of the bandfiltered periodic pulse trains can be analyzed, an accurate discrimination of the repetition frequency is possible, but as soon as the frequency analyzing is no longer complete, the relative jnd_g increases quickly until eventually the frequency discrimination is determined by changes in the envelope of the waveform of the stimuli. At the end of chapter 3 it is shown that the position of the frequency discrimination curve with respect to the n-axis can be determined for normal hearing subjects in a relatively short time. The spread appears to be fairly small.

The role of any possible intermodulation products (combination tones) generated in the ear is further investigated in chapter 4. The masking of the low frequency side of the stimuli has only a slight influence on the frequency discrimination and at any rate a smaller influence than a uniform masking. Pulsation-threshold patterns of stimuli, consisting of a group of higher harmonics with a small frequency separation, show that under certain conditions the level of combination tones is less than would be expected on the basis of the level of separately audible combination tones. It is concluded that the combination tones play a minor role in the frequency discrimination of the signals used.

In chapter 5 the frequency discrimination capacity of perceptively hearing impaired persons is determined for the same basic stimuli as a in chapter 3. On the average the hearing impaired persons appear to have a less accurate frequency discrimination capacity than normal hearing persons, both for pure and for complex tones. A connection between the jnd_f for pure tones and the hearing loss at that frequency cannot be precluded but is subject to some doubts. Much more striking is the fact that the characteristic frequency discrimination curve often deviates drastically from the normal shape. The chance to find a normal frequency discrimination curve decreases with increasing hearing loss and for higher filter frequencies. On the basis of the conclusions of chapter 3. changes in the frequency discrimination curve are considered to be disturbances of the frequency analyzing capacity in the frequency region concerned. No clear relation has been found between a deviating frequency discrimination capacity and a decreased speech intelligibility.

A determination of psychophysical tuning curves for the same hearing impaired persons, described in chapter 6, makes it possible to compare the merely qualitative conclusions about the frequency analyzing capacity from the frequency discrimination data with another measure of the frequency analyzing capacity. With increasing hearing loss a gradual blunting of the normally sharp tip of the tuning curve is observed. This tip altogether vanishes at a hearing loss of about 40 dB. With greater hearing losses other changes in the shape of the tuning curves are found in a great number of cases, such as a w-shaped pattern, overmasking and a strong upward spread of masking. A comparison of the frequency discrimination curves with the psychophysical tuning curves of the same subjects shows that there is considerable agreement as regards the changes in the frequency analyzing capacity. However, there are also deviations: an abnormal tuning curve can go with a fairly normal frequency discrimination curve. These differences are ascribed to the fact that the psychophysical tuning curves of hearing impaired persons are more complicated than those of normal hearing persons, and cannot be compared with electrophysiologically measured tuning curves without more ado.

Summarizing, it can be said that this investigation has amply proved that there is a considerable decrease of the frequency analyzing capacity in case of a perceptive hearing loss of cochlear origin and that this goes with a decrease of the frequency discrimination capacity. As the experimental data compiled cannot in any way be inferred from the usual clinical audiological data, particularly for the individual case, they create the possibility of enlarging the insight in perceptive hearing impairment.

SAMENVATTING

Frekwentie-discriminatie en frekwentie-analyse zijn twee verschillende vermogens van het auditief systeem. Frekwentie-discriminatie slaat op het kunnen onderscheiden van niet gelijktijdig klinkende tonen wat betreft hun frekwentie, terwijl frekwentie-analyse het vermogen is om een geluid in zijn bestanddelen te kunnen ontleden. Frekwentie-analyse wordt vooral bepaald door de eigenschappen van het auditieve filter, waarvan men aanneemt dat het in het binnenoor gesitueerd is. Voor normaalhorende proefpersonen zijn beide vermogens reeds vrij uitvoerig onderzocht. Voor slechthorenden heeft tot voor kort alleen frekwentie-discriminatie enige aandacht gekregen. Algemeen wordt aangenomen dat in geval van een perceptief gehoorverlies van cochleaire aard het frekwentie-analyserend vermogen verminderd is. Preciese gegevens ontbraken echter toen deze studie begonnen werd, vooral ook wat betreft relaties met andere gevolgen van perceptieslechthorendheid. Het is bv. aannemelijk dat voor een goed spraakverstaan onder ongunstige omstandigheden een goed frekwentie-analyserend vermogen nodig is. Met het onderhavige onderzoek is geprobeerd een bijdrage te leveren tot een beter inzicht in de discriminatieve en analytische vermogens van het pathologische gehoororgaan. Hiertoe zijn frekwentie-discriminatie experimenten uitgevoerd en zgn. psychofysische tuning curves bepaald.

Door gebruik te maken van geluidsignalen die samengesteld zijn uit een groep hogere harmonischen, is het mogelijk een verband te leggen tussen frekwentie-discriminatie en frekwentieanalyse. In dit onderzoek wordt het juist waarneembare verschil in herhalingsfrekwentie (jnd_g) van bandgefilterde periodieke impulsreeksen bepaald. De mate waarin de samenstellende harmonischen van dit signaal geanalyseerd kunnen worden hangt o.a. af van de verhouding tussen herhalingsfrekwentie en filterfrekwentie.

Eerst wordt in hoofdstuk 3 voor een beperkt aantal geoefende, normaalhorende proefpersonen uitvoerig onderzocht in hoeverre en op welke manier het beperkte frekwentie-analyserend vermogen van het perifere gehoororgaan in de resultaten van het frekwentie-discriminatie experiment weerspiegeld wordt. Er blijkt een karakteristiek verband te bestaan tussen de relative jnd_g enerzijds en de verhouding tussen filterfrekwentie f en herhalingsfrekwentie g anderzijds: een curve bestaande uit twee plateaux van constant, maar onderling sterk verschillend discriminatie

niveau met een overgangsgebied daartussen. Veranderingen in de filterkarakteristiek, zoals een bandbreedte variatie van 1/3- naar 1/1-octaaf en veranderingen in de flanksteilheid van 50 tot 150 dB/oct, hebben weinig of geen invloed op deze karakteristieke curve. Voor zeer steil afvallende filters wordt de relatieve jnd_g echter vrijwel onafhankelijk van de herhalingsfrekwentie. Het toevoegen van ruis beïnvloedt het frekwentie-discriminatie vermogen in ongunstige zin. Het toenemen van de jnd_g bij afnemende signaal-ruisverhouding blijkt voor stimuli met een laag harmonisch getal n (n = f/g) anders te verlopen dan voor stimuli met een hoog harmonisch getal. De overgang ligt ongeveer bij n = 14. Wanneer de te vergelijken impulsreeksen door op verschillende frekwenties afgestemde bandfilters worden gevoerd, zodat slechts onderscheid gemaakt kan worden op basis van een toonhoogte vergelijk, wordt eenzelfde frekwentie-discriminatie curve als boven gevonden. Uit de verzamelde gegevens wordt geconcludeerd dat de vorm van de karakteristieke frekwentie-discriminatie curve in belangrijke mate bepaald wordt door het beperkte frekwentie-analyserend vermogen van het gehoor: zolang de samenstellende harmonischen van de bandgefilterde periodieke impulsreeksen geanalyseerd kunnen worden is een nauwkeurig onderscheid in de herhalingsfrekwentie mogelijk, maar zodra de frekwentie-analyse niet meer volledig is, neemt de relative jnd_g snel toe totdat uiteindelijk het frekwentie-onderscheid bepaald wordt door veranderingen in de omhullende van de golfvorm van de stimuli. Tenslotte wordt in hoofdstuk 3 aangetoond dat de ligging van de karakteristieke frekwentie-discriminatie curve t.o.v. de n-as in betrekkelijk korte tijd kan worden vastgesteld voor ongeoefende normaalhorende proefpersonen. De spreiding blijkt vrij gering te zijn.

De rol van eventueel in het oor gevormde intermodulatieproducten (combinatietonen) wordt in hoofdstuk 4 nader onderzocht. Het maskeren van de laagfrekwente zijde van de stimuli door het toevoegen van ruis beïnvloedt de frekwentie-discriminatie weinig en in ieder geval minder dan een uniforme maskering. Pulsatiedrempelpatronen van stimuli bestaande uit een groep hogere harmonischen met een geringe frekwentiescheiding, laten zien dat de sterkte van combinatietonen onder bepaalde omstandigheden minder is dan op grond van een extrapolatie van de sterkte van afzonderlijk hoorbare combinatietonen verwacht zou worden. Er wordt geconcludeerd dat de combinatietonen voor de frekwentie-discriminatie van de gebruikte geluidsignalen een ondergeschikte rol spelen.

In hoofdstuk 5 wordt voor ongeoefende slechthorenden wier gehoorverlies van zuiver perceptieve aard is, het frekwentie-discriminatie vermogen bepaald voor dezelfde basis-stimuli als in hoofdstuk 3. Gemiddeld blijken de slechthorenden een minder nauwkeurig frekwentie-onderscheidingsvermogen te hebben voor zowel zuivere als complexe tonen dan ongeoefende normaalhorenden. Een samenhang tussen de jnd_f voor zuivere tonen en het gehoorverlies bij die frekwentie kan niet worden uitgesloten, maar is toch wel aan twijfel onderhevig. Veel opvallender is echter het feit dat de karakteristieke frekwentie-discriminatie curve vaak drastisch afwijkt van de normale vorm. De kans om een normale frekwentie-discriminatie curve te vinden neemt af voor toenemend gehoorverlies en voor hogere filterfrekwenties. Op basis van de in hoofdstuk 3 getrokken conclusies worden veranderingen in de frekwentie-discriminatie curve beschouwd als een verstoring van het frekwentie-analyserend vermogen in het betreffende frekwentie gebied. Er is geen duidelijk verband gevonden tussen een afwijkend frekwentie-onderscheidingsvermogen en een verminderd spraakverstaan.

Een bepaling van psychofysische tuning curves bij dezelfde slechthorenden, beschreven in hoofdstuk 6, maakt het mogelijk de slechts kwalitatieve gevolgtrekking omtrent het frekwentie-analyserend vermogen uit de frekwentie-discriminatie gegevens te toetsen aan een andere maat van het frekwentie-analyserend vermogen. Met toenemend gehoorverlies wordt een geleidelijk afstompen van de normaal scherpe tip van de tuning curve geconstateerd. Deze tip is geheel verdwenen bij gehoorverliezen van ca. 40 dB. Bij grotere gehoorverliezen worden bovendien in een groot aantal gevallen andere vormveranderingen van de tuning curve gevonden, zoals een w-vormig patroon, overmaskering en een sterke verbreding ook naar de hoge frekwenties. Een vergelijking van de frekwentie-discriminatie curves met de psychofysische tuning curves bij dezelfde proefpersonen leert dat er wat betreft de veranderingen in het frekwentie-analyserend vermogen een aanzienlijke overeenstemming bestaat. Er worden echter ook afwijkingen gevonden; zo kan een abnormale tuning curve samengaan met een vrij normale frekwentie-discriminatie curve. Deze verschillen worden toegeschreven aan het feit dat psychofysische tuning curves van slechthorenden gecompliceerder zijn dan van normaalhorenden en niet zonder meer vergelijkbaar zijn met electrofysiologisch gemeten tuning curves.

Samenvattend heeft dit onderzoek ruimschoots aangetoond dat er sprake is van een beduidende vermindering van het frekwentie-analyserend vermogen in geval van een perceptief gehoorverlies van cochleaire aard en dat dit gepaard gaat met een vermindering van het frekwentie-discriminatie vermogen. Aangezien de verzamelde experimentele gegevens met name voor het individuele geval op geen enkele wijze uit de gebruikelijke klinische audiologische gegevens kunnen worden afgeleid, leveren zij als zodanig de mogelijkheid het inzicht in perceptieslechthorendheid te verdiepen.

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